DRAFT Report On:

Devils Lake Outlet
Analysis of Effects of the Planned Operation of the Devils Lake Outlet on Groundwater Levels along the Sheyenne River

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Minneapolis, Minnesota

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Table of Contents

List of Tables

List of Figures

List of Plates

List of Appendices

1.0 Introduction

The U.S. Army Corps of Engineers (USACOE) St. Paul District contracted Barr Engineering Company (Barr) to perform an evaluation and analysis of the effects on groundwater from a proposed project plan for a Devils Lake outlet that could result in sustained high stage in the Sheyenne River. Hydrologic changes that affect groundwater levels or groundwater quality may affect land uses adjacent to the river. The study area is shown on Figure 1.

In 1998, the USACOE, along with the United States Geological Survey (USGS), initiated a study to look at the relationship between streamflow and groundwater in the Sheyenne River valley from Sheyenne to Kindred, North Dakota. Monitoring wells, with automated water level readers, were installed along lines perpendicular to the river. A total of four sites along the Sheyenne River were selected for examining the effects of river stage on groundwater levels. The sites are near the towns of Sheyenne, Cooperstown, Kathryn and Walcott, North Dakota. The sites were selected along river reaches representing different topographic and physiographic settings. Monitoring generally covers the period from 1998 to 2001 depending on when the sites were initiated and when additional wells were installed.

Generally, precipitation and flooding affect water levels in the surficial aquifer. During high stages in the river, groundwater flow gradients near the river can reverse, causing water to flow from the river into the adjacent surficial aquifer deposits. The proposed Devils Lake outlet design includes a constrained operation plan, not to exceed 450 mg/L sulfates or 600 cubic feet per second (cfs) channel capacity at the insertion point. For purposes of this analysis the outlet was assumed to operate at 300 cfs from May 1 through November 30 regardless of river stage. The outlet flow will be in addition to any flow currently in the river.

1.1 Planned Project and Potential Effects

The proposed projects (Devils Lake Outlet) are anticipated to cause increases in the stage of the Sheyenne River during parts of the year. The projected river stage conditions for this project are modeled data (HEC-5) provided to Barr by the USACOE, encompassing a period of 50 years. The scope of this study is for the groundwater effects of this project to be evaluated in terms of groundwater levels and water quality.

1.2 Study Objectives and Approach

The objective of this study is to predict the effects of increased river stages on groundwater levels and groundwater quality for the Devils Lake Outlet along the Sheyenne River. The effects of the proposed project are presented separately for four monitored sites (Sheyenne, Cooperstown, Kathryn and Walcott) and two unmonitored sites in the Sheyenne River Delta aquifer (referred to in this report as "Delta 1" and "Delta 2" in this report). The locations of these sites are shown on Figure 2. The analysis results are expanded to address the remainder of the river. The following technical issues are addressed:

1. The magnitude and duration of the effects of increased river stages on groundwater levels and the location and distance from the river where the effects are found. Reasonably anticipated seasonal variations are included in this evaluation.

2. The magnitude and duration of the effects of increased river stages on groundwater flow directions and the potential long-term effects of changes in the groundwater flow direction, with respect to the river are evaluated. The primary issue here is to determine whether or not gaining portions of the Sheyenne River may become losing portions due to the proposed project.

3. The magnitude and duration of the potential changes in groundwater quality, due to groundwater mixing and/or changes in groundwater direction resulting from changes in river water quality and/or changes in river stages are addressed. Seasonal variations are considered, where practical.

4. The local contributions to the groundwater system at the monitored sites, such as precipitation and overland flow, which have the primary (and maybe the only) effect on the groundwater levels are included in the evaluation.

The results of this study are intended for use by the USACOE. This report has been prepared as a stand-alone source of information, to the extent practical, on the pertinent aspects of groundwater hydrology and their application to the particular problem. Assumptions and limitations are discussed as fully as possible and the presentation is intended for those without a specialized background in hydrogeology and groundwater mechanics. A glossary of terms and a list of symbols are provided in Appendix B of this report.

The approach to evaluating the effects of the proposed project on groundwater level and quality is based primarily on a previous study performed by Barr in the Sheyenne Delta aquifer (Barr, 1999). That study focused on the effects of two proposed projects (Devils Lake Outlet and Baldhill Pool raise) on groundwater levels and groundwater quality in the Sheyenne River delta aquifer. The primary concern of the study was the effect of increased river levels on wild orchids that are found in the area. The results of the study showed that the effects of increased river stage generally extended about 1,500 feet from the river and the effects on groundwater quality were restricted to only a few feet over a part of the year.

The study described in this report examines a slightly different release scenario and covers areas adjacent to the Sheyenne River that extend beyond the delta areas of Ransom and Richland counties. The study approach includes the following:

?? Review previous studies on the geology and hydrogeology of the Sheyenne Delta aquifer and transmissive deposits adjacent to the river upstream of the delta aquifer and synthesize these studies into a coherent conceptual understanding of how groundwater flows and interacts with changes in river stage, precipitation, evapotranspiration, etc. Copies of reports that describe these previous studies were provided to Barr by the USACOE. Additional resources were also sought out, such as bibliographies and the Internet.

?? Construct a series of "profile models" of groundwater flow, roughly perpendicular to the Sheyenne River, parallel to regional groundwater flow direction. The computer code MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996) was used to construct these models.

?? The MODFLOW profile models incorporated hydrogeologic parameters that had been measured or estimated by others in previous studies. These parameters are believed to be representative of conditions along each profile, depending upon where the profile is situated in the aquifer.

?? Simulations of the conditions of the proposed project were performed using the MODFLOW profile models. Transient simulations were deemed to best represent the project conditions. The simulation results yielded projections of the change in the water table elevation as a function of distance from the Sheyenne River. A comparison was made between the response of the water table near the River to river stage fluctuations with and without the proposed Devils Lake Outlet release of approximately 300 cfs.

?? Simulation of the incursion of river water into the adjacent surficial aquifer was performed using the solute transport program MT3D in conjunction with MODFLOW. HEC-5 data for predicted sulfate concentrations were used for a two-year period to examine the incursion of sulfate into the aquifer. Sulfate was chosen because it is generally conservative (i.e. not reactive with the aquifer media) and would best estimate the maximum incursion of river water.

2.0 Site Setting

2.1 Location and Physiography

The subject area of this analysis is covers two provinces: (1) the Sheyenne River Delta, including portions of the Sheyenne National Grassland in southeastern North Dakota's Red River Valley and (2) the alluvial river valley of the Sheyenne River from approximately Sheyenne to Lisbon, North Dakota. A map of physiography is shown on Figure 3

2.1.1 Sheyenne River Delta and Sheyenne National Grassland

The Sheyenne National Grassland encompasses 67,293 acres (105 square miles) and is managed by the U.S. Forest Service. It is depicted as a tallgrass prairie but a "Sandhill Prairie" is more accurate (Sieg and Wolken, 1998). The elm-basswood forest type found associated with the Sheyenne River is the most westerly extension of this forest type in the United States. Other plant species unique to North Dakota occur on the Grassland and in many circumstances, along springs that flow into the Sheyenne River.

The flat expanse of the Red River Valley is a result of the former presence of glacial Lake Agassiz, which was a shallow lake left by the retreating ice sheet during the last glaciation, some 10,000 years ago. The glacial lake drained southward through a channel now occupied by the Bois de Sioux River and a chain of lakes and marshes. The lake water then flowed east, roughly following the present course of the Minnesota River.

For the most part, the deposits at the bottom of Lake Agassiz were lacustrine (i.e. originating in a lake) clays, with some sandier beach deposits along the periphery of the lake. The lake clays were deposited on glacial till, which is also very clayey. The glacial till was deposited at the bottom and sides of the ice sheets that pre-dated the lake. A notable exception to the deposition of lake clays was in the vicinity of where the Sheyenne River entered glacial Lake Agassiz. The Sheyenne River discharged considerable amounts of sand into the lake, forming an expansive delta. When Lake Agassiz eventually drained away, a flat sand plain, resting on a flat expanse of clay, was left behind. This sandy plain is now referred to as the Sheyenne Delta and occupies about 750 square miles of Richland and Ransom Counties.

Recent erosion has been very slight and the only conspicuous topographic change in Richland County since the drainage of the lake has been the formation of sand dunes on the Sheyenne Delta.

The Sheyenne Delta surface is covered with sand dunes over much of its extent and the topography is strongly rolling. The highest dunes border the Sheyenne River valley, where the local relief may exceed 50 feet. Most of the dunes are stabilized by vegetation but there is considerable movement of sand wherever the vegetal cover is broken. The northeastern edge of the delta is marked by a conspicuous steep slope, prominent at the Cass-Richland County boundary but it becomes less prominent southward and is barely visible south of Colfax (Baker, 1967).

The Sheyenne Delta is an extensive deposit in Richland County (550 of the 750 square miles of the Delta is in Richland County). The sand and silt of the Sheyenne Delta are as much as 200 feet thick. A notable exception to this thickness is near the Sheyenne River, where the stream has cut down into the deltaic deposits to form a broad river valley, nearly a mile wide. Within this valley, the deltaic deposits have been reworked and mixed with finer grained sediment, brought in from upstream areas.

The Sheyenne Delta is an important aquifer in Richland and Ransom Counties, due to its high sand content, which makes it very permeable. Melting snow and rain infiltrate very rapidly, resulting in almost no formation of drainage patterns, except very near the Sheyenne River valley. Groundwater generally flows toward the Sheyenne River, which is a gaining stream through most of its reach through the Sheyenne Delta (Paulson, 1964). Groundwater also is removed from the aquifer by evapotranspiration during the growing season. The Sheyenne delta aquifer contains an estimated 4 million acre-feet of ground water in storage and receives about 50,000 acre-feet of recharge during a year of average precipitation (Baker and Paulson, 1967).

2.1.2 Sheyenne River Alluvial Valley

The Sheyenne River originates in Sheridan County and flows eastward through Wells, Benson, Eddy, and Nelson Counties before flowing southward through Griggs and Barnes Counties and again eastward through Ransom and Richland Counties before flowing northward through Cass Counties where it discharges into the Red River north of Fargo. The Sheyenne River valley described here includes the section of river that extends from its origin in Sheridan County to the vicinity east of Lisbon where it meets the Sheyenne River Delta, which has been described above.

The Sheyenne River Valley is located on drift plains left behind as a result of the retreating Wisconsinan glaciers. The regional geology includes a glacial till over much of the area. In portions of Eddy, Nelson, and Griggs Counties, glacial outwash deposits and end moraine complexes exist as a result of the retreating glaciers. Recent erosion along the Sheyenne River has created a valley that cuts into the regional glacial geology and at some locations into the underlying bedrock shales

(Pierre Formation, Niobrara Formation, and Carlile Formation). River deposits within the valley include clays, silts, sands, and cross-bedded sands.

2.2 Climate

Climate is continental in type, characterized by short summers and long, cold winters. Summer temperatures above 90-degrees Fahrenheit are common and winter temperatures are often as low as 20-below Fahrenheit. The average annual precipitation is about 20 inches, three-fourths of which falls as rain in May through October (Baker, 1967; Armstrong, 1981). Somewhat more than 82 percent of the annual evaporation (about 30 inches) also occurs during the same period (Armstrong, 1981.) During the late 1980's the area experienced drought conditions with below-normal precipitation. Since 1993, above-average precipitation has been the norm.

2.3 Topography and Physiographic Setting

2.3.1 Sheyenne River Delta

Richland and Ransom Counties are in the Central Lowland province of the Interior Plains. The eastern part of Richland County is in the Red River Valley physiographic division and 300 square miles in the southwestern part of Richland County and much of Ransom County are in the Drift Prairie physiographic division. The Red River Valley can be divided into the Sheyenne Delta, which occupies approximately 750 square miles, and the Lake Agassiz plain (Baker, 1966).

Land overlying the Sheyenne Delta consists of relatively flat lake plain and gently rolling hills (Strobel and Radig, 1997). The steep banks and hills are adjacent to the Sheyenne River and were produced by surface erosion and eolian dune formation. The north end of the Sheyenne Delta stands about 100 feet above the lake plain; the delta grades outward into the plain. Outside of the dune areas, the ground is gently rolling to nearly flat. The Sheyenne River crosses the delta in a steep-sided valley that is as much as 120 feet deep and a mile wide (Baker, 1966). The area west of the Sheyenne Delta is part of a physiographic region called the "Drift Prairie", which is an area of high relief (50 to 75 feet in a square mile) and nowhere does it approach the levelness of the lake plain.

The Delta is characterized by a generally low-relief, east- to northeast-sloping surface that is covered by irregular, partly stabilized hills of windblown sand. Local relief on some of the dunes exceeds 75 feet. The dunes tend to be within one to two miles of the Sheyenne River. Shallow depressions, 1 to 10 feet deep, and sand dunes as much as 85 feet high have been formed by wind action (Baker, 1982). A series of small hills and swales on the Sheyenne Delta gives the landscape a hummocky appearance. The Sheyenne River valley is entrenched as much as 120 feet below the delta surface and exposes an incomplete cross section of the deltaic stratigraphy. The northeast edge of the delta is marked by a 75-foot high, wave-cut scarp (i.e. the delta was cut by the wave action of glacial Lake Agassiz) that becomes less pronounced southward.

The hummocky nature of the delta surface is limited mostly to the Sheyenne National Grassland and appears to be obscured to a great extent in areas of the delta that are outside of the National Grassland by recent surface disturbance; probably cultivation. The hills and swales are likely important mechanisms for recharge to the aquifer (Strobel and Radig, 1997; Shaver, 1998) and appear to control the occurrence of western prairie fringed orchid (Sieg and Wolken, 1998).

The surface of the Sheyenne Delta is noticeably devoid of developed drainage patterns. Surface drainages (other than the Sheyenne River) are poorly developed because the permeable soils that developed on the deltaic deposits cause generally rapid infiltration of snowmelt and rain through the sandy soils into the aquifer (Strobel and Radig, 1997). A number of unnamed streams enter the Sheyenne River from the Delta—most of these minor streams are only a few miles long and although spring fed, some are dry during a part of every year. Good subsurface drainage precludes the existence of permanent ponds on the delta but marshy areas are numerous in wet seasons (Baker, 1967). In very wet years, water in some of the deeper depressions may be surface expressions of the water table.

Several man-made drainage ditches were observed on the Sheyenne Delta during a site visit on August 13, 1998 (This visit is described in detail in Barr (1999)). Most of these ditches ran north-south, with discharge to the Sheyenne River. Smaller laterals drained into these large ditches from croplands, though the croplands are not tiled. All of the major drainage ditches, including those running east-west on either side of major paved County roads, had standing or flowing water in them.

2.3.2 Sheyenne River Alluvial Valley

The Sheyenne River Valley is located within the Western Lake section of the Central Lowland physiographic province. The Sheyenne River migrates through the Upper, Middle, and Lower Sheyenne Watersheds. It also migrates through the regional Northern Glaciated Plain Ecoregion (Level III) and locally the Drift Plains and Glacial Outwash Ecoregions (Level IV). The regional topography is characterized as flat to gently rolling landscape composed of glacial drift. Locally, the topography is described as subtle undulating over a thick mantle of glacial till with a high concentration of temporary and seasonal wetlands. Ancient river channel depressions and relict lake features comprise areas where glacial outland and end moraine complexes exist in Eddy, Nelson, and Griggs Counties. The topography along the Sheyenne River exhibits steep terraces where the river has eroded into and through the glacial drift and till material.

Surface drainage into the Sheyenne River is mainly through intermittent streams with the exception of Baldhill Creek and Big Coulee, which are perennial streams. The Baldhill Dam is located downstream of the confluence of Baldhill Creek and Sheyenne River directly north of Valley City. Additionally dams on the Sheyenne River are located near Harvey, Sheyenne, Tolna, and Lisbon. Many minor dams are located on intermittent tributaries to the Sheyenne River.

2.4 Land Use

Cattle grazing is the main use of public lands (Sheyenne National Grassland). On private land, land uses are crop production (corn and sunflowers, most of which are irrigated from the surficial aquifer with lesser amounts of soybeans, small grains, cattle forage, and potatoes) and cattle grazing. Corn and potatoes (that thrive in coarser-grained irrigated soils) are found most commonly on the western part of the Delta. The deltaic deposits are also homogeneous in this area.

2.5 Geologic History

The following is a brief description of the geologic history of the area.

The deepest (and oldest) rocks underneath the Sheyenne River are Precambrian (i.e. greater than about 570 million years old) crystalline rocks, such as granite. These rocks were heavily eroded at the beginning of the Cretaceous Period (about 135 million years ago). The Williston Basin (the center of which is near Williston, North Dakota) began to slowly sink and fill with sediments washed in from the erosion of the Precambrian crystalline rocks. Richland County is on the edge of the Williston Basin and was probably a source area for these basin sediments (Baker, 1967).

As the Williston Basin continued to sink, the Cretaceous seas invaded the area, covering an irregular and deeply weathered ground surface with sea water. Advance of the sea to the east was slow and very shallow water covered the area. The oldest sedimentary rocks in the area (Dakota Sandstone) were deposited at this time in a near-shore, beach setting. The irregular distribution and varying thickness of the Dakota Sandstone suggests that many knobs and hills of the Precambrian granite protruded as islands in the shallow sea. The sea probably retreated briefly after deposition of the sand that now makes up the Dakota Sandstone and erosion probably removed much of the deposit from the eastern part of the area (Baker, 1967)

Later, water completely covered the area and black mud (Graneros Shale) was deposited in quiet, brackish water. A few thin beds and lenses of fine sand suggest that the shoreline was not far away. Younger deposits (Greenhorn Formation) contain much interbedded limestone and were probably formed in somewhat deeper water with better circulation. Younger Cretaceous rocks that are present further west (Niobrara, Pierre, and other formations) are absent under Richland County. Probably at least some of these rocks were deposited in the area but were subsequently eroded (Baker, 1967).

After the retreat of the Cretaceous seas, the area again was subjected to erosion for a very long period of time (from about 65 to 2 million years ago). Many of the Cretaceous rocks were stripped away and the weathered Precambrian rocks were exposed again in the deepest valleys. This last long period of erosion was terminated with the advance of the Pleistocene glaciers, beginning about two million years ago. It was during the Pleistocene that most of the present landscape was formed.

The area was covered several times by sheets of glacial ice during the Pleistocene Epoch (about 2 million to 10,000 years ago). Each ice sheet probably left deposits of drift and each succeeding ice sheet probably removed and redistributed part of the deposits of its predecessor. The deposits of the various ice sheets are so similar in lithology that there is no ready means of distinguishing between them. Great thicknesses of glacial drift were deposited and by the time of the last glacial retreat the original topography was completely buried. A portion of the last ice sheet broke off and melted in place and the stagnant ice left characteristic topographic features in the southwestern corner of Richland County. The stagnant ice deposits were overridden by a minor re-advance of the glacier and then the final withdrawal of the ice began (Baker, 1967).

The regional slope in eastern North Dakota was to the northeast and as the last ice sheet retreated to the north it blocked the drainage. A large proglacial (i.e. in front of the glacier) lake (Lake Agassiz) was formed in eastern North Dakota and western Minnesota. Most of Richland and Ransom Counties are within the Lake Agassiz basin. At its maximum, Lake Agassiz extended from northeastern South Dakota to northern Manitoba (more than 550 miles) and had an average width of 150 miles. The greatest depth of Lake Agassiz in Richland County (difference between lowest point on the lake plain and the highest beach) was about 150 feet (Baker, 1967). The ancestral Sheyenne River flowed into Lake Agassiz a few miles east of what is now the town of Lisbon.

Lake Agassiz had an outlet to the south through a channel now occupied by the Bois de Sioux River and a chain of lakes and marshes. The outlet continued westward through the River Warren, which generally followed the course now occupied by the Minnesota River. Water flowing out of the lake eroded the bottom of the channel and this deepening of the outlet caused a general lowering of the water level in the lake. The materials in the floor of the channel were not homogeneous; consequently the rate of erosion was not uniform. During periods of rapid erosion, the lake level fell rapidly; during periods of slow erosion, the lake level changed slowly and well-defined shorelines were formed. As the ice continued to retreat, lower outlets were uncovered to the northeast and Lake Agassiz gradually receded from Richland and Ransom Counties. Possibly a re-advance of the glacial ice blocked the northern outlets and caused the lake to be refilled to the level of the southern outlet. The effect of the draining and refilling was slight; a few scattered deposits of silt on the lake plain may have been left behind during the second stage of the lake (Baker, 1967).

Many of the surficial features of Richland and Ransom Counties were formed in Lake Agassiz. During the highest stage of the lake, a well-defined shoreline (referred to as the "Herman shoreline") was created and an extensive delta was formed at the mouth of the Sheyenne River. This delta prograded (i.e., grew) from west to east, depositing sand and silt as it built out into the lake, much like modern deltas, such as the Nile Delta, do today. Baker (1967) has several block diagrams that illustrate how the delta deposits likely formed. As the ice sheet dwindled and the lake was drained, other beaches were formed at lower levels and parts of the courses of four of these lower beaches can be traced through Richland County. During the life of Lake Agassiz, wave action smoothed the lake floor and a blanket of clay and silt was deposited in the deeper parts of the basin (Baker, 1967).

When the glacial ice far to the north finally melted and Lake Agassiz was drained, the lake plain had essentially the form that is seen today. Recent erosion has been very slight and the only conspicuous topographic change since the drainage of the lake has been the formation of sand dunes on the Sheyenne Delta and in the vicinity of Hankinson. These dunes probably were formed very soon after the drainage of the lake and have changed little in recent times. The Sheyenne River has cut through the deltaic deposits, forming a broad meander-belt valley in which the deltaic sands have been reworked and mixed with silts and clays brought into the area from upstream. Oxbow lakes have formed where meanders have been abandoned. At least one terrace level is present in the river valley (a terrace represents an earlier elevation of the river).

2.6 Stratigraphy

Stratigraphy refers to the sequence of rock deposits, with the deepest rocks generally being the oldest and younger rocks deposited on top. The oldest rocks (Precambrian granites) are igneous and metamorphic, whereas all younger rocks in the area are sedimentary in origin. A sedimentary rock is simply a lime mud, clay, silt, sand, or gravel that has been cemented into a stone through a process called "diagenesis" that is substantially influenced by time and pressure during burial. The Pleistocene glacial deposits are generally not yet formed into rock and are referred to as "unconsolidated." Baker (1967) provides a stratigraphic column for Ransom and Richland Counties that summarizes the general stratigraphy of the area:

Age	Unit	Description	Thickness (feet)
Quaternary (recent)	Alluvium	Silt and clay on flood plains of modern streams	0-40
Quaternary (Pleistocene)	Glacial Drift	Glacial till, glaciofluvial deposits, and glacial lake sediments	154-490
Cretaceous	Greenhorn Fm.	Black limey shale, generally contains minute white “specks” of calcium carbonate; interbedded with white to buff limestone	0-212
Cretaceous	Graneros Shale	Black shale, locally with streaks and lenses of white sand; often marine fossils	0-160
Cretaceous	Dakota Sandstone	White quartz sand with interbedded varicolored sandy shale, siltstone, and clayey sandstone	0-238+
Cretaceous (?)	Undifferentiated rocks	Light gray to moderate yellowish-green “nodular” sand, interbedded with varicolored clay	0-61
Precambrian	Undifferentiated crystalline rocks	“Granite.” Generally deeply weathered in upper part	?

A map of Quaternary geology is shown on Figure 4 and a map of bedrock geology for the study area is shown on Figure 5.

2.7 Geology of the Sheyenne Delta and Associated Deposits

The Sheyenne Delta: covers about 750 square miles, of which 550 is in Richland County. The Delta is crossed by the Sheyenne River, which is deeply entrenched into the delta. The northeastern edge of the delta is marked by a conspicuous steep slope, prominent at the Cass-Richland County boundary but it becomes less prominent southward and is barely visible south of Colfax. Near

Wyndmere, there is no surface expression of the delta edge and the limits of the delta must be mapped on the basis of the changes in lithology (Baker, 1967).

The surface of the Sheyenne Delta is covered with sand dunes over much of its extent (though they are most prevalent near the Sheyenne River) and the topography is strongly rolling in the dune areas. The highest dunes border the Sheyenne River valley, were the local relief may exceed 50 to 75 feet. Most of the dunes are stabilized by vegetation but there is considerable movement of sand wherever the vegetal cover is broken (Baker, 1967).

The deltaic deposits generally become finer from west to east across the Sheyenne Delta, which probably is the result of finer sediment being carried farther into Lake Agassiz before settling out and being deposited. Grain size in the deltaic deposits generally increases in both the upward and shoreward (southwest) directions because of the progradation of the delta into glacial Lake Agassiz (Cowdery and Goff, 1994). Along the western extent of the Sheyenne Delta in Ransom County, the deposits are generally medium to coarse sand. Near the Richland-Ransom County boundary, the delta sediments are primarily fine to medium sand but the average grain size decreases eastward. Near the eastern edge, the predominant lithology is very fine sand and silt with some interbedded clay (Baker, 1967).

Stratification is well exposed in only one known locality, near the eastern edge of the delta (west edge of Sec. 14, T 136 N, R 51 W), where fine sand, silt, and clay are interbedded and the sand and silt are cross stratified (Baker, 1967). The most common type of stratification is ripple lamination. Some silt and very fine sand beds are strongly contorted on a small scale. The mode of formation of these contortions is not known but such contortions, as well as the ripple laminations, are common features of deltaic and floodplain deposits (Baker, 1967).

As the delta advanced into Lake Agassiz, it built out over its own bottomset beds and over existing lake-floor deposits. Because of this, it is impossible to distinguish in test holes between delta bottomsets and lake-floor deposits of essentially the same composition; therefore a boundary cannot be established between delta and lake-floor deposits (Baker, 1967). Pleistocene lacustrine clays about 100 feet thick underlie the Sheyenne Delta aquifer throughout the study area (Downey and Paulson, 1974). The clays, which are plastic and have low hydraulic conductivity, form a relatively impermeable basal unit to the aquifer. A thick sequence of Pleistocene-age till and stratified drift underlies the lacustrine clays (Downey and Paulson, 1974).

Pleistocene glacial drift (sediment deposited by glaciers) mantles the entire area underneath the delta and along its margins; the known thickness of the drift, including the deposits of glacial Lake Agassiz, range from 154 to 490 feet (Baker, 1966). Glacial drift, representing several ice sheets, may be present but cannot be differentiated except in a few places. All of the surficial features can be attributed to the last ice sheet (Mankota advance); local zones of oxidized till, extensive bodies of buried outwash, and buried lake silts are the only indications of the presence of older drift in the subsurface (Baker, 1966).

The delta deposits can be divided into three units (Baker, 1967): (1) a lower unit of silt interbedded with clay and sand, which is thickest near the eastern margin of the delta and thins westward; (2) an upper unit of well-sorted sand, which is thickest in the west and thins eastward; and (3) a thin layer of wind-blown sand, which covers the entire delta. The lower silty unit is more than 150 feet thick at the eastern edge of the Delta, less than 50 feet thick near the Richland-Ransom County boundary, and is entirely absent near the western edge of the Delta in Ransom County. The sand unit is as much as 100 feet thick near the Richland-Ransom County boundary, and is entirely absent near the eastern edge of the Delta in Ransom County. Its average thickness in Richland County is about 60 feet. The grain size of the sand generally decreases eastward from medium and coarse along the Richland Ransom County boundary to very fine in the eastern part of the Delta near Walcott. The thickness of the wind-blown surficial sand is generally less than 10 feet but may be as much as 50 feet in the highest dunes.

The greatest thickness of sand penetrated during test drilling on the Sheyenne Delta was 107 feet in test hole 2185 (135-52-21ccc) but it is questionable whether this figure should be taken as the thickness of the delta deposits at this point - the drill passed from sand into silty clay and the hole was stopped after drilling only a few feet into the clay before reaching the underlying till. The greatest known thickness of sand, silt, and clay; that is, the greatest known depth to glacial till is 198 feet penetrated in test hole K-2R (136-51-7ddd). The average depth to till is 150 feet. The delta sand is only 45 feet thick near the southern edge of the Delta and has no clay or silt under it (Baker, 1967).

3.0 Previous Studies

An annotated bibliography of previous studies that were provided to Barr is presented in Appendix A. These previous studies are believed to encompass most, if not all data and information that now exists on the hydrogeology of the Sheyenne Delta aquifer that is pertinent to this study. These previous studies are summarized below.

Paulson, Q.F., 1964. Geologic factors affecting discharge of the Sheyenne River in southeastern North Dakota: USGS Professional Paper 501-D, p. D177-181.

?? Throughout much of its length the Sheyenne River is fed almost wholly by overland runoff from glacial till. However, in the reach 75 to 145 miles upstream from its junction with the Red River of the north, the Sheyenne drains groundwater from sand deposits in the Sheyenne Delta, into which its valley is deeply incised. Discharge measurements made in the fall of 1963 indicated an average gain of 28.8 cfs in this reach.

Baker, C.H., Jr., 1966. Geology and ground-water resources of Richland County, North Dakota, Part II, Basic data: North Dakota Geol. Survey Bull. 46 and North Dakota State Water Comm. County Ground Water Studies 7, 170 p.

?? This is a compendium of water-quality data, well construction information, and well logs for Richland County. Includes map of well locations. Cited in other reports.

Baker, C.H., Jr., 1967. Geology and ground water resources of Richland County, Part 1, Geology: North Dakota Geological Survey Bulletin 46 and North Dakota State Water Commission County Ground Water Studies 7, 45 p.

?? Richland County comprises an area of approximately 1,450 square miles in the southeastern corner of North Dakota. About one-fifth of the county is in the Drift Prairie physiographic division; the remainder is in the Red River Valley (basin of glacial Lake Agassiz) physiographic division. The stratigraphy of the sedimentary rocks underlying the Pleistocene deposits is relatively uncomplicated. Cretaceous Dakota Sandstone lies unconformably on the Precambrian crystalline basement. The Graneros Shale and the Greenhorn Formation, both of Late Cretaceous age, overlie the Dakota in most of the county, and no indurated rocks younger than the Greenhorn are present.

- ?? Pleistocene glacial drift mantles the entire county; the known thickness of the drift, including the deposits of glacial Lake Agassiz, range from 154 to 490 feet. Drift representing several ice sheets may be present but cannot be differentiated except in a few places. All of the surficial features of the county can be attributed to the last ice sheet (Mankota advance); local zones of oxidized till, extensive bodies of buried outwash, and buried lake silts are the only indications of the presence of older drift in the subsurface.

- ?? The major surficial features of the Drift Prairie in the county are stagnation moraine, a large body of overridden pitted outwash, and an ice-marginal drainage channel. Minor features include end moraine, ground moraine, and kames.

- ?? The flat expanse of the Red River Valley is interrupted by the Sheyenne Delta and by the major shorelines of glacial Lake Agassiz. The Sheyenne Delta is an extensive deposit in Richland County and an important aquifer. It covers 550 square miles and consists of sand and silt as much as 200 feet thick. The lake-floor deposits, where present, may include two distinct lithologies, but the upper unit is thin and irregularly distributed. Few Pleistocene fossils have been found in Richland County, and most of the available material is of little value for age determinations

Baker, C.H. Jr. and Q.F. Paulson, 1967. Geology and ground water resources of Richland County, North Dakota, Part III - Ground water resources: North Dakota Geological Survey Bulletin 46 and North Dakota State Water Commission County Ground Water Studies 7, 45 p.

- ?? Water supplies in Richland County are obtained mainly from ground water. The most important sources are the shoreline deposits of glacial Lake Agassiz. These deposits contain two main aquifers— identified as the Sheyenne delta aquifer and the Hankinson aquifer, which have a combined area of about 400 square miles. They consist of well-sorted deposits of sand that are at least 50 feet thick in most places and as much as 100 feet thick near the western boundary of the county. Grain-size analyses indicate possible well yields of at least 50 gallons per minute in most places and as much as 1,000 gallons per minute in a few places. The aquifers are relatively undeveloped and water levels are only a few feet below land surface. The Sheyenne Delta aquifer contains an estimated 4 million acre-feet of groundwater in storage and receives about 50,000 acre-feet of recharge during a year of average precipitation. The water in the Sheyenne Delta and

Hankinson aquifers generally contains less than 500 parts per million dissolved solids, and, although hard, is usable for most purposes.

?? Aquifers of less importance are associated with the till deposits and in the bedrock formations, chiefly the Dakota Sandstone. The aquifers in or associated with the till generally are smaller and less productive. Aquifers in the bedrock yield water that is of rather poor chemical quality. However, wells developed in these sources may be capable of yielding 500 gallons per minute in places.

Downey, J.S. and Q.F. Paulson, 1974. Predictive modeling of effects of the planned Kindred Lake on ground-water levels and discharge, southeastern North Dakota: USGS Water-Resources Investigations 30-74, 22 p.

?? A digital model was used to describe a groundwater system in glacial deltaic deposits near Kindred, North Dakota, and to predict the effects of a planned lake on groundwater levels and groundwater discharge. A digital computer was used to solve the finite-difference equations for groundwater flow. The model analysis delineated an area of about 140 square miles that would be affected by rising water levels as a result of the lake. The rise of water levels depends on time and hydraulic properties of the aquifer. The maximum projected rise in water levels should occur in about 50 years. Evapotranspiration from the water table is presently near maximum and therefore the projected water-level rise will not be controlled by evapotranspiration. Existing artificial drains will be effective in limiting the extent of water-level rise.

Armstrong, C.A., 1979. Ground-water basic data for Ransom and Sargent Counties, North Dakota: North Dakota Geological Survey Bulletin 69 - Part II and North Dakota State Water Commission County Ground-Water Studies 31 - Part II, 637 p.

?? This is a compendium of water-quality data, well construction information, and well logs for Ransom and Sargent Counties. Includes map of well locations. Cited in other reports.

Bluemle, J.P., 1979. Geology of Ransom and Sargent Counties, North Dakota: North Dakota Geological Survey Bulletin 69 - Part I and North Dakota State Water Commission County Ground-Water Studies 31 - Part I, 84 p.

?? Ransom and Sargent Counties, located at the eastern edge of the Williston Basin are underlain by 500 to 1,800 feet of Paleozoic and Mesozoic rocks that dip gently to the northwest. The Cretaceous Belle Fourche, Greenhorn, Carlile, Niobrara, and Pierre Formations lie directly beneath the glacial drift, and the Sheyenne River, especially in northwestern Ransom County. The Pleistocene Coleharbor Group, which covers most of the area, consists mainly of glacial, fluvial and lake sediment. The Coleharbor Group averages about 200 feet thick but it is as much as 400 feet thick near Gwinner. The Holocene Oahe Formation occurs in parts of the area, chiefly sloughs, river bottomland, and dune fields. It consists mainly of alluvial and eolian sediment.

?? Most of the two-county area is part of the Glaciated Plains, an area characterized by nearly level to undulating topography. Rolling to steep land is found along the Sheyenne River valley, on the Prairie Coteau in southeastern Sargent County, in areas of sand dunes in the eastern part of Ransom County, and western Sargent County, and in areas of intense ice thrusting, which are prominent in western Sargent County.

?? Several distinct till layers that have been identified in Ransom and Sargent Counties attest to repeated glacial advances, both prior to and during Wisconsinan time. Following the earliest flooding of western Sargent County by glacial Lake Dakota, a re-advance of the glacier resulted in large-scale thrusting. The early glacial Lake Agassiz flooded eastern parts of the two counties, resulting in discontinuous lake and shore sediments above the Herman level. Later, the Sheyenne Rive built a large delta into the lake while it stood at the Herman level. After Lake Agassiz drained, wind erosion built large dunes on the Sheyenne Delta.

Armstrong, C.A., 1981. Supplement to: Predictive modeling of effects of the planned Kindred Lake on ground-water levels and discharge, southeastern North Dakota: USGS Open-File Report 81-646, 15 p.

?? A digital model was used to describe a ground-water system in glacial deltaic deposits near Kindred, North Dakota, and to predict the effects on ground-water levels of a planned lake at 950-, 960-, 970-, 984-, and 995-foot stages. This model is a supplement to an earlier model of the ground-water system for a planned lake at the 984-foot level (Downey and Paulson, 1974). The model analysis indicates that only the area within about 2 miles of the present Sheyenne River would be affected by rising water levels as a result of a lake stage at 995 feet. The rise of water levels depends on time and hydraulic properties of the aquifer. The maximum projected rise in water levels is expected to occur in about 50 to 100 years. Evapotranspiration and existing drains will be effective in limiting the extent of water-level rise. Consequently, the area affected by rising water levels at each lake stage will be much smaller than that shown by the earlier model at the 984-foot stage.

Armstrong, C.A., 1982. Ground-water resources of Ransom and Sargent Counties, North Dakota: North Dakota Geological Survey Bulletin 69 - Part III and North Dakota State Water Commission County Ground-Water Studies 31 - Part III, 51 p.

?? Groundwater in Ransom and Sargent Counties is available from glacial-drift aquifers of Quaternary age and from the Dakota aquifer system of Cretaceous age. Glacial-drift aquifers with the greatest potential for development are the Spiritwood aquifer system and the Brampton, Elliott, Gwinner, Elglevale, Milnor Channel, Oakes, Sheyenne Delta, and Sand Prairie aquifers. Properly constructed wells in the more permeable parts of these aquifers will yield from 500 to 1,5000 gallons per minute. A total of about 3,000,000 acre-feet of water is available from storage in the glacial-drift aquifers. Water from the glacial-drift aquifers varies in chemical quality. Dissolved solids concentrations in samples from these aquifers range from 203 to 4,670 milligrams per liter.

?? The top of the Dakota aquifer system underlies Ransom and Sargent counties at depths that range from 500 to 1,000 feet below land surface. Water in the Dakota is under sufficient head to flow at land surface in most parts of the two-county area. Unrestricted flows from wells tapping the aquifer system generally are less than 10 gallons per minute but may be as much as 50 gallons per minute. Water in the Dakota aquifer system generally is a sodium sulfate type and has dissolved-solids concentrations ranging from 2,170 to 3,340 milligrams per liter.

Cowdery, T.K. and K. Goff, 1994. Nitrogen concentrations near the water table of the Sheyenne Delta aquifer beneath cropland areas, Ransom and Richland Counties, North Dakota: Proceedings of the North Dakota Water Quality Symposium, Fargo, North Dakota, March 30-31, 1994, North Dakota State University Extension Service, p. 89-102.

?? Purpose: land-use study to examine the human activities and natural factors affecting the quality of shallow (within 3 meters of land surface) groundwater underlying agricultural areas on the glacial, near-shore deltaic-facies deposits of the Sheyenne Delta. The Sheyenne Delta was selected for this study because it is a surficial aquifer and is susceptible to contamination from the land surface.

?? Homogeneous land use patterns and local groundwater discharge to the Sheyenne River simplify groundwater constituent sources and make the Sheyenne Delta an excellent land-use study site. Cattle grazing is the main use of public lands (Sheyenne National Grassland). On private land, land uses are crop production (corn and sunflowers, most of which are irrigated from the surficial aquifer with lesser amounts of soybeans, small grains, cattle forage, and potatoes) and cattle grazing.

?? The paper is a review of both the 1993 nitrate-nitrogen data collected by NAWQA study and historical nitrate-nitrogen data. Purpose of study is to (1) describe nitrate concentrations near the water table beneath cropland areas after the early part of the 1993 growing season (2) relate nitrate concentration to spatial changes in land use and geology; groundwater recharge and depth to water table; and precipitation and (3) to suggest explanations for these relations.

?? Samples were collected from 29 randomly selected wells during July and August 1993. Seven existing and 22 newly constructed wells form the network sampled for this study. The seven existing wells were installed by the NDSWC or the USGS during 1963 or 1972. Rainfall on the Delta during the 1993 growing season was 166 percent of average for the last 31 years.

?? Historical nitrate concentrations come from 70 samples by the NDSWC and 3 by USGS. These data were grouped into (1) High Nitrate (> 0.68 mg/L); (2) Medium Nitrate (0.23-0.68 mg/L) and (3) Low Nitrate (<0.23 mg/L). Samples with high to medium concentrations cluster on the west (beach) side of the delta, south and east of the Sheyenne River and west of the Sheyenne National Grassland.

?? Progradation of the delta into a water body resulted in a general trend of increasing grain size in both the upward and beachward directions. Therefore the Delta aquifer should generally be hydraulically less conductive toward the east-northeast - this trend is documented by Downey and Paulson (1974) who also noted that the entire delta thins to the west as the Lake Agassiz basin approaches the surface.

?? Shallow, high-production irrigation wells and crops such as corn and potatoes (that thrive in coarser-grained irrigated soils) are found most commonly on the western part of the delta. The deltaic deposits are also most homogeneous in this area.

?? Because nitrogen application rates are greatest on potatoes and corn corps, it is reasonable to expect that the shallow ground water in the western part of the delta has the highest concentrations of nitrate in the study area. Nitrates may also be concentrated by pumping high-nitrate groundwater for irrigation.

?? As water table rises, the time required for infiltrating water to reach the water table (lag time) decreases. This lag time increases in December when water table depth increases. Microbial denitrification in groundwater is not a likely mechanism for lower nitrate concentrations in wet years. DOC concentrations are too low.

Hopkins, D.G., 1996, Hydrologic and abiotic constraints of soil genesis and natural vegetation patterns in the sandhills of North Dakota: Ph.D. thesis, North Dakota State University.

?? The Sheyenne Delta aquifer is a calcium-bicarbonate type water characterized by low salinity and sodium content. Water from the Dakota aquifer enters the Sheyenne Delta aquifer only as flowing wells. The water is seven times more saline and nearly 40 times higher in sodium than water in the Sheyenne Delta aquifer. The Dakota aquifer is classified as a sodium-sulfate type but chloride is the dominant anion in 10 of 74 wells tested.

?? Two new land use practices are occurring in the sandhills: one is management response to a natural, though undesired, example of plant succession, (leafy spurge has infested approximately 19% of the Sheyenne National Grasslands and significantly reduced rangeland productivity and stocking rates) the other a result of economic opportunities in agriculture.

?? Both the USFS and private landholders in the sandhills are applying 2,4-D and picloram (Tordon) to control leafy spurge. The threat these herbicides pose to groundwater quality has not been assessed in the Sandhills. In the past, local irrigation has been dedicated to corn for grain or silage, but irrigated potato production has increased rapidly in the Sandhills during the last few years. Corn acreage is being converted to potato production and several large storage facilities have been erected. Ransom County acreage planted in irrigated potatoes was virtually nil in the mid-1980s and was about 1134 hectares in 1994. The number of application permits to withdraw water from the Sheyenne delta aquifer for irrigation has increased markedly.

Strobel, M.L. and S.A. Radig, 1997. Effects of the 1993 flood on water levels and water quality in the Sheyenne Delta aquifer, southeastern North Dakota, 1993-94. USGS Water-Resources Inv. Report 97-4163, 43 p.

?? This study was conducted to evaluate the effects of precipitation and flooding on water levels in the Sheyenne Delta aquifer and to evaluate the variations in water quality that are related to the precipitation and flooding. Water-level, streamflow, and water-quality data collected prior to July 1993 were assumed in this study to be representative of pre-flood conditions. Data collected from July 1993 through May 1994 were used to evaluate the groundwater response. The study found that the largest water level rises in the aquifer are associated with low-relief areas, where rapid infiltration of snowmelt, runoff, and precipitation can take place. Snowmelt and precipitation in high-relief areas, typically in areas near the river, either travel as surface runoff to low-relief areas or to the river or infiltrate to the water table and flow in the direction of the steep hydraulic gradient toward the river.

?? The water table elevations were found to change little during frozen winter months. Delayed recharge may be taking place in areas with thicker unsaturated deposits, due to delayed recharge percolation to the water table. During March, water levels in the aquifer rose by more than 2 feet in some areas as substantial recharge took place over large parts of the aquifer, in response to precipitation and snow melt. Water levels then generally declined during the first half of April as snow melt declined. Reversals of groundwater flow very near the river were inferred from water-level data during high stage conditions in the river (i.e. bank storage). These reversals were "temporary" (less than one month) in duration and very localized near the river (less than one mile from river). Overall hydraulic gradients to the river decreased slightly during this period, due both to higher river stage and to increased infiltration over the aquifer. The authors estimate that high stage levels on the Sheyenne River in July and August 1993 probably caused water-table gradients near the river to reverse and water from the river flowed into the aquifer as temporary bank storage. "Direct effects of the 1993 flood on water levels in the aquifer probably were limited to the area adjacent to the river." "However, excessive precipitation associated with the flood probably affected water levels throughout the aquifer. Water levels in two observation wells in the aquifer indicate that the water table generally was about 2 feet higher during the fall and winter of 1994 than during the fall and winter of 1993." (P. 35).

?? The aquifer is generally a calcium bicarbonate or calcium magnesium bicarbonate type, with dissolved-solids concentrations ranging from 269 to 1,820 mg/L. "No discernable differences existed between the pre-flood data and the post flood data for both dissolved-solids and chloride concentrations." (P. 35) The only pesticide detected was picloram and it was randomly distributed (reflecting local land use).

Shaver, R., June 9, 1998. North Dakota State Water Commission Office Memo to David Spryncznatyk, State Engineer, through Milton O. Lindvig, Director, Water Appropriations Division - Conditional Water Permit Application #5188, 31 p.

?? On November 24, 1997, Ransom-Sargent Water Users, Inc. (Don Smith) submitted a conditional water permit application to the State Engineer to divert 550 acre-feet of groundwater annually from points of diversion located in the W1/2 of S. 11, T 134N, R 54W at a maximum pumping rate of 1,300 gpm. The diversion is for municipal-rural-domestic use. At a hearing on February 10, 1998, a letter from Allyn J. Sapa of the U.S. Fish and Wildlife Service was submitted that expressed concern over potential adverse impacts on the western fringed orchid (*Platanthera praeclara*) as a result of the proposed appropriation. A letter from Steve Williams of the US Forest Service was also submitted that expressed concern over potential impacts on the orchid and plant productivity in the nearby Sheyenne National Grasslands. A letter from Richard D. Nelson of the US Bureau of Reclamation requested that the State Engineer perform an analysis to delineate the maximum area of drawdown influence from the proposed pumping and the effects on groundwater seeps.

?? To a great extent, the recharge to the Sheyenne Delta aquifer can be characterized as depression focused (Lissey, 1968). During the winter, a frost zone develops at or near the water table. Snow accumulates in depressions and on adjacent topographic-high areas. In the spring, snow melts before the frost zone dissipates. Snowmelt originating in the upland areas accumulates in depressions from surface runoff because of the inability to infiltrate through the frost zone. Ponded water in depressions infiltrates downward to the saturated zone after the frost zone dissipates.

?? Recharge to the Sheyenne Delta aquifer takes place primarily during the spring. During most summer months, recharge to the aquifer is minor because potential evapotranspiration exceeds precipitation. Summer precipitation events generally are not large enough to overcome soil-moisture deficits and generate recharge. Occasionally, during the fall precipitation exceeds both evapotranspiration and soil-moisture deficits and recharge takes place. Even when recharge does not occur during the fall, soil-moisture deficits generally are reduced, significantly affecting the magnitude of the following spring recharge event.

?? Depth to the water table is generally less than 8 feet. The capillary fringe of water table and root zone are coupled. As a result, natural discharge from the Sheyenne Delta aquifer is due, in large part, to evapotranspiration. Armstrong (1982) suggests in a year with normal precipitation, between 14 and 50 percent of precipitation that infiltrates to the aquifer as recharge eventually discharges to the Sheyenne River. Thus, about 40 to 86 percent of natural discharge from the Sheyenne Delta aquifer is due to evapotranspiration.

?? In the central part of the grassland (away from the Sheyenne River) the hydrogeologic setting is conducive to the development of numerous local flow systems (cells) in which underflow may be insignificant. Within each local flow system, recharge is from relatively direct infiltration of precipitation and local runoff (snow melt) that occurs primarily during the spring. The capillary fringe of the water table and root zone are coupled and therefore discharge primarily is from evapotranspiration that takes place during the growing season. "Thus, movement of ground water is largely vertical, and flow paths are relatively short."

?? William M. Schuh, Hydrologist Manger, NDSWC summarized storativity calculations for Hecla, Hamar, and Ulen soils (5 sites) in the Oakes aquifer study area in Dickey-Sargent counties (December 31, 1990 memo). Specific yield was calculated from total porosity, laboratory wetted porosity, and fielded wetted porosity. Results of study indicate little difference in specific yield between the zone of pedogenesis and the underlying coarse parent materials. Mean values of specific yield by layer were close to 0.25. Based on this, specific yield for Sheyenne Delta aquifer is 0.25 in the study area.

?? Water levels remain relatively stable during the winter when recharge does not occur and evapotranspiration is greatly reduced.

?? The average annual irrigation application rate from 1977 through 1996 is 9.7 inches per acre in the western portion of the aquifer (permit application area). Compared to the mid to late 1980s, irrigation water use decreased significantly beginning in 1993, due to wetter, cooler growing seasons. Water-level fluctuations caused by irrigation withdrawals are masked by water-level fluctuations caused by natural variations in recharge and discharge (primarily evapotranspiration) as dictated by changing patterns of climate.

?? The State Engineer allocated groundwater with a "sustainable yield" management framework for the Sheyenne Delta aquifer because the annual recharge in many years is relatively large in relation to the volume of water in storage (i.e., water is renewable). The sustainable yield in the Sheyenne Delta aquifer is equal to the long-term average volume of groundwater discharged by evapotranspiration and underflow to the Sheyenne River. "Thus, as water is pumped from the aquifer the volume of water discharged by evapotranspiration and to the Sheyenne River will be diminished. Diminishment of groundwater evapotranspiration requires the decoupling of the plant root zone from the capillary fringe of the water table."

?? The Sheyenne Natural Grasslands occupy about 110 square miles in the central part of the Sheyenne Delta aquifer (about 28 percent of the aquifer), from which groundwater withdrawals (pumping) will not likely occur.

?? The State Engineer has approved an annual appropriation of 19,123.9 acre-feet from the Sheyenne Delta aquifer. This appropriated volume is 15 percent of the average annual recharge of groundwater in the practical development area of the delta.

?? Allocations of appropriation are not made using digital groundwater flow models. Instead, an on-going assessment of aquifer response as related to a specific amount of groundwater development is used. Assessment of aquifer response is accomplished by water-level, water-quality, and water-use monitoring, coupled with an evaluation of climate data, aquifer properties and boundary conditions.

?? Recommended the appropriation as long as the right of prior appropriators will not be unduly affect; the proposed means of diversion or construction are adequate; the proposed use of water is beneficial; and the proposed appropriation is in the public interest.

Sieg, C.H. and P.M. Wolken, 1998. Dynamics of a threatened orchid in flooded wetlands (DRAFT): submitted to 16th North Am. Prairie Conference, July 26-29, 1998, Kearny, NE, 21 p.

?? One of the three largest metapopulations of the western prairie fringed orchid (Platanthera praeclara) occurs on the Sheyenne National Grassland, in southeastern North Dakota. Our study was initiated in 1993 to quantify the effect of flooding on individual orchid plants. A total of 66 plants (33 flowering and 33 vegetative) growing in standing water were permanently marked in 1993; their status was checked at the end of the growing season in 1993 and in subsequent growing seasons (1994-1996). Most (70%) of the flowering plants persisted through the 1993 growing season; those that did not were shorter ($P=0.001$) and had a higher percentage of their stalk submerged through the growing season ($P<0.02$). Only one vegetative plant persisted through the 1993 growing season. The ability of the flowering plants to persist in standing water was attributed to their greater height which allowed some portion of the plant to remain above the water and produce photosynthates needed to produce next season's shoot bud and immature root system. Flowering plants persisted through the first growing season with as much as 75% of their stalk submerged in water. In 1994, only four plants reappeared; in 1995 only one plant reappeared aboveground. None of the plants that did not persist through 1993 reappeared in 1994 or 1995. By 1996 none of the marked plants were observed aboveground. Although flooding is detrimental to the survival of vegetative plants, its impact must be viewed in a larger context and include data over several years. It is likely that flooding creates suitable moisture conditions on higher landscape positions, provides and important mechanism for seed dispersal, and is one of several natural catastrophic events that plays a significant role in perpetuating these wetland systems and associated species.

4.0 Summary of Barr (1999) Study

A previous study of the effects of proposed releases from Devils Lake and the Baldhill Dam Pool raise on groundwater levels in the Sheyenne River Delta aquifer was performed in 1999 by Barr. Because (1) the Sheyenne River Delta aquifer is a portion of this study and (2) because the methodologies and findings of the 1999 study are directly applicable to this study, the Barr (1999) study is described in somewhat more detail than the other references. The profile modeling approach and the findings of the effects of temporal increases in the stage of the Sheyenne River provided important insight into the approach used for this study.

The Sheyenne Delta area, the Sheyenne River valley, and the Sheyenne National Grassland were toured on August 13, 1998. In attendance were Ray Wuolo (Barr Engineering Company), Robert Anfang and Mark Meyers (U.S. Army Corps of Engineers - St. Paul District). A portion of the afternoon tour was led by District Ranger Brian Stots (U.S. Forest Service) and Bill Pearson of the U.S. Fish and Wildlife Service.

4.1 Analysis of Hydraulic Effects

Hydraulic effects of the two projects on groundwater levels were analyzed by developing numerical profile models along six non-linear cross sections through the Sheyenne Delta aquifer using the U.S. Geological Survey's finite-difference groundwater flow code MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996). The cross sections were non-linear because they were oriented along groundwater flow paths, defined by Paulson (1964). (Note: Cross-sections 2 and 4 in the 1999 study are cross-sections Delta 1 and Delta 2 of this study).

The profiles extend from the groundwater divide of Paulson (1964) to the center of the Sheyenne River, which is a hydraulic boundary. Profiles were not constructed to simulate areas north of the river because the flow path north of the river is much shorter, and because the area where wild orchids grow is south of the River. It was assumed that the groundwater effects on the north side of the river would be similar to those described for the south side of the river.

4.1.1 MODFLOW Profile Model

Each of the six profile models (one for each section) consisted of 1 cell wide (width of one meter, perpendicular to the flow direction), 193 cells long, and 8 layers tall. Layer 1 (top layer) was of indeterminate thickness because the system is unconfined. The one-cell width is a standard profile modeling practice (Anderson and Woessner, 1992). Layers 2 through 6 were 5 meters thick and Layers 7 and 8 were 10 meters thick. All layers were horizontal. Because each profile had the same number of cells in the direction of flow but each was of different length, the cell length varied, depending on the section.

The profile model orientation used in the Barr (1999) study is termed a "slice" orientation because it is a vertical slice along a flow path. With the slice orientation, no adjustment to hydraulic conductivity, specific yield, or recharge is needed to compensate for the slicing of the aquifer into a section (Anderson and Woessner, 1992). The "moving boundary" problem of a varying water table is not at issue either since the layers are allowed to convert from confined to unconfined if the water table drops into a given layer. Recharge was applied to the uppermost active node (nodes that are not saturated are made inactive). The MODFLOW grid was designed and the parameters were entered into the model using the integrated modeling environment ModIME.

4.1.2 Initial Conditions

The difference between the two modeled events was that the Baldhill Pool raise scenario was a randomly-timed flood event of approximately 70 days duration whereas the Devil's Lake outlet had a recurring, seven-month long duration. Because of the difference in the types of scenarios represented by these events, different approaches were required in setting up the baseline conditions.

A steady-state condition, with typical values for recharge and evapotranspiration and a river stage equal to the starting stage for the flood event was chosen for setting the initial conditions for the Baldhill Pool raise simulation. The baseline case used the steady-state heads for initial conditions and imposed a series of river stage changes typical of a 100-year flood under current conditions. The effects of the Baldhill Pool raise were then simulated using a second series of river stage changes reflecting the effects of the pool raise. In this way, the effects of differences in river stage throughout the flood event could be compared directly. This approach isolated the effect of interest: the only boundary condition that is changing in the simulation is the river stage. Consequently, the effects of different time-varying river stages as caused by the Baldhill Pool raise versus the baseline condition were determined directly by comparing the results of the two simulations.

The Devils Lake outlet scenario was on a time scale (seven months) over which variations in recharge rate, evapotranspiration rate, and river stage could not reasonably be assumed as constant and were therefore be incorporated in the simulation. Since the system is dynamic and the question was "what are the effects of an increase in discharge over a specified period of time in a typical year" the first task was to determine what the typical year looks like. If the baseline transient simulation starts from an arbitrary steady-state condition, part of the water level response might reflect the system moving toward equilibrium with its new boundary conditions. To prevent this, the simulation of the typical year was run several times in succession, with the final water levels from one year forming the starting conditions for the following year. It was found that after about four or five years, a pattern was set up in which the water levels at the end of the simulation were approximately equal to those from the beginning of the simulation, which was the desired effect. In this way, differences between the baseline response and the response caused by the higher river stages due to operation of the Devils Lake outlet could be isolated from other causes.

4.1.3 Transient Analysis

In order to determine the effects of the proposed projects on a typical spring cycle, it was necessary to simulate the superposition of elevated river stage (above and beyond the typical effects) on the typical spring cycle and determine the effects in terms of deviations from the typical condition. As such, this is a transient (time-dependent) problem. The question was: how much additional change in groundwater level is predicted to result from the additional increase in river stage? This is the same question that is asked in this study.

4.1.4 Water Quality Effects

The effects of excursion of Sheyenne River water into the Sheyenne Delta aquifer were not directly evaluated in this study. Instead, hydraulic effects were evaluated, which could be used to place an extremely conservative limit on the potential extent of excursion of Sheyenne River water into the aquifer. Principally, the distance from the River where the predicted water-level increases would be zero was conservatively taken as the maximum extent of excursion of river water.

4.2 Data and Assumptions Used in MODFLOW Analyses

4.2.1 Hydraulic Conductivity, Aquifer Base Elevation, and Specific Yield

Hydraulic conductivity values for the Sheyenne Delta aquifer were based on Plate 3 of Downey and Paulson (1974). A digital Surfer® map was constructed from these data. Aquifer base elevation varied across the site and was gleaned from various sources. The grid values that result from the geostatistical routines became the basis for assigning parameters to profile models.

Once the six profiles were delineated, the cell coordinates (UTM NAD 27) along each profile were determined using ArcView® GIS (geographic information system). The Surfer® grids for hydraulic conductivity and aquifer base elevation are also in UTM NAD 27 coordinates. Using a residual query technique in Surfer®, the hydraulic conductivity and aquifer base elevation for each grid cell along each profile were assigned. For those cells (principally in Layers 7 and 8) that had elevations predominantly below the aquifer base elevation, a hydraulic conductivity of 0.1 meters/day was assigned to represent the underlying clay. A vertical anisotropy value of 0.1 was used (i.e. the vertical hydraulic conductivity was assumed to be 10 percent of the horizontal hydraulic conductivity). This is a value typically used to model sand aquifers (Anderson and Woessner, 1992).

The specific yield value used in all simulations was 0.15, which is slightly lower than the 0.2 value used by Downey and Paulson (1974). This is considered a conservative value. A storage coefficient value of .0001 was used for layers that did not contain the phreatic surface. These storage parameters are deemed to be on the low side and will therefore yield a "worse-case" transient response to increases in river stage.

4.2.2 Recharge

For the simulations of the Devils Lake Outlet, typical monthly precipitation values were acquired from the Northern Prairie Wildlife Research Center via the Internet at:

http://www.npwrc.usgs.gov/resource/othrdata/climate.

The data are included in Appendix C – these data formed the basis for recharge estimates in this study. Since several previous studies (e.g., Downey and Paulson, 1974; Armstrong, 1982; Strobel and Radig, 1997) indicate that most of the recharge takes place immediately following frost-out and during the spring months precipitation falling in December through February were not applied until March to simulate the effects of frost preventing infiltration.

The USACOE provided hydrographs for the Lisbon gage and Kindred gage showing river stages throughout a series of floods with and without the Baldhill Pool raise. In general, the effect of the Baldhill Pool raise would be to lower the peak stage of the flood and to prolong its duration. The simulations were based on statistical evaluations of the recorded river stages at the two gages. No direct correlation with precipitation was possible. Since the objective of this project was to determine the effects in terms of deviation from typical conditions, a typical annual precipitation of 497 mm (19.57 in/yr) (Sieg and Wolken, 1998) was applied to both simulations as the recharge value in terms of 497 mm/365 days, or 1.36 mm/day for the 70-day simulation period. Recharge was found to not be a substantially important parameter during this simulation because evapotranspiration essentially cancels out its effect.

4.2.3 Surface Topography

The topography of the ground surface is generally not a parameter in most groundwater models but it was used in the modeling of the Barr (1999) study as a control on spring formation (i.e. where groundwater elevations are higher than the ground surface) and evapotranspiration (which is a function of depth to groundwater at a given location).

Ground surface elevation was obtained from digital elevation maps (DEMs) developed by the U.S. Geological Survey and downloaded from the Internet at http://www.gis.swc.state.nd.us/. These DEMs were converted to UTM NAD 27 coordinates and incorporated into an ArcView® GIS project. The accuracy of the elevation data was considered sufficient for the intended use because the modeling was intended to reflect the relatively large vertical difference between the upland areas and the river (a difference of up to 120 feet, Strobel and Radig, 1997, p.7).

For the portion of each profile that transected the Sheyenne River valley, drain cells were placed in the appropriate layer with heads equal to the ground-surface elevation. In this way, seepage and springs could be simulated if the water table elevation in any of these cells exceeded the ground-surface elevation. For the most part, this did not take place during the simulations.

In setting up the drain package input file, no drain invert was specified at an elevation below the maximum river stage for that simulation. For example, on Table F-4, the maximum river stage for the simulation of the Baldhill Pool raise at that cross-section was 317.69 m MSL. This was used as a default invert elevation for those cells in which the surface elevation was lower than this maximum river stage. This was done to prevent a drain cell located near the river, which would be inundated at that maximum river stage, from removing water from the system. This prevented the creation of unrealistic boundary conditions using the drain cells.

4.2.4 Evapotranspiration

The Evaporation Package in MODFLOW was employed in simulating both the Devils Lake Outlet and the Baldhill Pool raise. Three parameters were required: (1) the maximum evapotranspiration potential; (2) the depth below which maximum evaporation no longer takes place; and (3) the depth beyond which the capillary fringe of the water table and the root zones are decoupled and groundwater evapotranspiration ceases (i.e., groundwater ET extraction depth). The ground surface elevation must also be known— this is described in the previous section.

The Evapotranspiration Package assumes an evapotranspiration removal rate equal to the maximum evapotranspiration potential between the ground surface and the depth at which the maximum no longer holds. This value was taken from Downey and Paulson (1974) as 7.16 feet. The depth at which evapotranspiration from the water table ceases was also taken from Downey and Paulson (1974) at 11.25 feet. From 7.16 feet downward to 11.25 feet, the evapotranspiration rate decreased linearly.

4.2.5 Sheyenne River Stage

4.2.5.1 Devils Lake Outlet

Typical monthly discharges and ratings tables for the Sheyenne River at the Lisbon gage and Kindred gage were acquired from the U.S. Geological Survey via the Internet at:

http://water.usgs.gov/cgi-bin/realsta.pl?huc=09020204.

The ratings table contained the information needed to convert from discharge to river stage. The river stage was interpolated between the two gages assuming a linear relationship with river mile. The effects of the Devils Lake outlet were modeled by adding 300 cubic feet per second of discharge to the monthly average values for the months of May through November (Table 2).

4.2.5.2 Baldhill Pool Raise

The USACOE provided stage-elevation curves for the various flood events for the Lisbon and Kindred gage, assuming the Baldhill Pool raise. The river stage was interpolated between the two gages assuming a linear relationship with river mile.

4.3 MODFLOW Simulation Results

4.3.1 Devils Lake Outlet

Except for Section 6, water level increases in all other sections were less than 0.1 feet (1.2 inches) at a distance of 1,500 feet from the Sheyenne River. There was essentially no effect of the Devils Lake Outlet project at a distance of 1,400 feet from the Sheyenne River for any of the six sections.

Based on the results for the six profile models, a plan-view map was developed that depicted the area along the Sheyenne River were the simulations predict that water levels in the aquifer will increase.

4.3.2 Baldhill Pool Raise

The maximum increase in the water table that resulted from the proposed Baldhill Pool raise was for the 100-year flood event. The maximum water level increase along all six sections was below 0.1 feet (1.2 inches) within a distance of approximately 750 feet of the Sheyenne River. At approximately 1,500 feet from the Sheyenne River, there was no discernable effect of the Baldhill Pool raise on water levels in the aquifer for the 100-year flood event.

4.4 Implications for Water-Quality Effects

The maximum increases in water levels in the aquifer that were predicted from the MODFLOW simulations were not reflective of the degree of incursion of Sheyenne River water. The distance of maximum incursion is undoubtedly very much closer to the River than the line that represents the maximum extent of water-level increase because a change in water level in the aquifer is not synonymous with a reversal in hydraulic gradient. The study indicates that, as an extremely (and unrealistic) worse-case condition, one can assume that the line of zero water-level increase corresponds to the maximum distance of incursion of Sheyenne River water

4.5 Study Conclusions

For the Baldhill Pool Raise

1. The maximum water-level increase in the aquifer, resulting from the Baldhill Pool raise, was predicted to occur during the 100-year flood event. At a distance of approximately 1,500 feet from the edge of the Sheyenne River, the maximum predicted water-level increase was less than 1.2 inches. At a distance of approximately 2,100 feet from the Sheyenne River, there was no effect of the Baldhill Pool raise on water levels.

2. Excursion of Sheyenne River water during the flood event must be less than the maximum extent of water-level effects in the aquifer. Although not specifically modeled as part of this study, it was concluded that it was very likely that the excursion of the river water during the flood event is limited to less than a few tens of feet from the River.

For the Devils Lake Outlet

1. At a distance of approximately 1,500 feet from the edge of the Sheyenne River, the maximum predicted water-level increase was less than 4 inches. At a distance of approximately 2,100 feet from the Sheyenne River, there was no effect of the Devils Lake Outlet on water levels.

2. Excursion of Sheyenne River water during the release of water from the Devils Lake Outlet must be less than the maximum extent of water-level effects in the aquifer. Although not specifically modeled as part of this study, the study concluded that it was very likely that the excursion of the river water during the flood event was limited to less than a few tens of feet from the River.

The Barr (1999) conclusions appear to be entirely consistent with observations and analyses made by others during previous studies. The study indicated that the river-stage increases predicted for the two proposed projects would not cause changes in groundwater levels beyond the immediate vicinity of the Sheyenne River. Groundwater quality impacts, if any, would be even more restricted the close proximity of the Sheyenne River.

The results of this study indicated that the hydraulic gradients as measured between points beyond the immediate vicinity of the Sheyenne River will be unaffected by the increased flow in the Sheyenne River resulting from the Devils Lake outlet and Baldhill Pool raise. The hydraulic gradient is directly related to flow in a steady-state, one-dimensional flow system. In a three-dimensional, transient flow system such as that in the Sheyenne Delta aquifer, flow is also affected by changes in storage within the aquifer (which tend to dampen the effect of transient pulses in the system), seepage (which removes water from the groundwater system), and evapotranspiration (which also removes water from the groundwater system). In other words, rising groundwater levels in the vicinity of the river do not automatically cause rising groundwater levels in the upland areas. Although the hydraulic gradient between a point in the upland and a point by the river may have been reduced, this does not necessarily cause a rise in groundwater level in the upland area because of increased evapotranspiration, seepage, and placement of water into storage in the aquifer in the areas experiencing rising water level.

5.0 Analyses of River Stage Changes on Groundwater

This study builds upon the approach initially developed in the Barr (1999) study that was applied to the Sheyenne River delta aquifer. In this study, the evaluation of impacts of river stage increases that are predicted to result from controlled releases of water from Devils Lake are extended to include areas along the Sheyenne River from discharge point at Peterson Coolie to downstream of the Sheyenne River delta aquifer.

As in the Barr (1999) study, the analysis approach used is the profile groundwater model. The USACOE directed Barr Engineering to evaluate groundwater level changes at four cross-section locations near Sheyenne, Cooperstown, Kathryn, and Walcott. Walcott is in the eastern portion of the Sheyenne River Delta aquifer but the other locations are in what is best described as a narrow alluvial valley, bounded and underlain by Cretaceous shales and/or low-permeability tills. Because the Sheyenne River delta aquifer is substantially different from the narrow alluvial valley aquifers that characterize the surficial aquifer upstream of Lisbon, two additional locations were included in this analyses – both in the Sheyenne River Delta.

The USACOE provided 50 years of model-generated, daily flows for projected stream flow conditions without the 300 cfs controlled discharge from Devils Lake and with the proposed Devils Lake discharge. These simulated flow data were generally for locations were a gaging station is present and a rating curve has been developed. The locations of gaging station are shown on Figure 6. A rating curve represents the relationship between stream flow and river stage. Rating curves for the gaging stations are in Appendix D.

The four locations (Sheyenne, Cooperstown, Kathryn, and Walcott) each have several monitoring wells that were installed in the surficial deposits by the U.S. Geological Survey. A record of water levels is available for these wells that encompasses approximately November 1999 to November 2001, although not all of the wells include data from this period. The water level data were collected with automated measuring devices and include multiple measurements from a single day. It is our understanding that these locations were chosen, in part, for monitoring wells because they were near gaging stations.

Although near gaging stations, the locations are not exactly at the gaging stations. This means that stage data must be interpolated for the stations. In some instances, such as Cooperstown, the gage and the monitor location are not far apart and interpolation is straight-forward. However, in some other cases, such as Sheyenne, the gage is a considerable distance from the monitoring point and extrapolation is required in order to estimate the stage levels.

The approach to evaluating the effects of the proposed Devils Lake discharge on groundwater levels and groundwater quality in the saturated deposits adjacent to the Sheyenne River was to:

?? Review previous studies on the geology and hydrogeology of the Sheyenne Delta aquifer and the alluvial aquifer upstream of the Delta and synthesize these studies into a coherent conceptual understanding of how groundwater flows and interacts with changes in river stage, precipitation, evapotranspiration, etc. Copies of reports that describe these previous studies were provided to Barr by the USACOE. Additional resources were also sought out, such as bibliographies and the Internet.

?? Construct a series of "profile models" of groundwater flow, roughly perpendicular to the Sheyenne River, parallel to regional groundwater flow directions, and spaced across the alluvial or Sheyenne Delta aquifers. The computer code MODFLOW and the pre- and post-processor Groundwater Vistas were used to construct these models.

?? The MODFLOW profile models incorporated hydrogeologic parameters that had been measured or estimated by others in previous studies. These parameters are believed to represent typical conditions for each profile model, depending upon where the profile is situated. In some locations, such as the Sheyenne River Delta, there is considerable site-specific information. In locations upstream of the Sheyenne River Delta, data and information is less complete and the selection of parameters and aquifer geometry is more uncertain.

?? Simulations of modeled river-stage conditions (1) without and (2) with the proposed projected were performed using the MODFLOW profile models. Transient simulations for a 10-year period were performed because of the fluctuation in river stage levels. The time increment (i.e. stress period) was one day. Thus, for each simulation, there were 7300 predictions of water levels along the profile model. The simulation results yielded projections of the change in the water table elevation as a function of distance from the Sheyenne River.

?? Simulated hydrographs and a map of the projected maximum extent of water-table change were developed from the MODFLOW results.

?? The solute transport code MT3D was used with MODFLOW to evaluate the incursion into the alluvial aquifer of a conservative (i.e. non-reactive) solute in the river. A two-year period was used for the evaluation. Model-predicted sulfate concentrations for the Sheyenne River (provided to Barr Engineering by the USACOE) were used. Predictions of the concentration of sulfate in the groundwater at various locations were made in order to ascertain the degree of incursion of river water and the time required for this water to be flushed back into the river from the aquifer.

The details of this analysis approach are described below.

5.1 Conceptual Hydrogeologic Model

The "conceptual hydrogeologic model" is a description of how groundwater in the Sheyenne Delta aquifer and the alluvial aquifer system upstream of the Sheyenne Delta is recharged, how groundwater is discharged, where groundwater flows, and how groundwater flow conditions are affected by hydraulic stresses, such as the change in river stage of the Sheyenne River. The conceptual hydrogeologic model is also a description of what factors are most important when considering the analysis of groundwater flow and what factors can be neglected without sacrificing confidence in predictions. The conceptual hydrogeologic model states the assumptions that become the basis for the computer models.

5.1.1 Recharge to the Aquifer

Previous studies in the area indicate that water enters the aquifer by: (1) infiltrating precipitation and snowmelt; (2) losses from drainage ditches (where the elevation of the water in the ditch is above the elevation of the water table); and (3) through "bank storage", which is a temporary discharge from the river to the alluvium and nearby portions of the aquifer during periods of elevated river stage.

The Sheyenne Delta aquifer and alluvial aquifer do not receive substantive amounts of water from underflow, originating beyond the limits of the aquifer. The lateral boundaries of the Sheyenne Delta aquifer are relatively well defined. The Delta is bounded by glacial drift on the west and south and grades into lacustrine sediments in the east and north (Strobel and Radig, 1997).

The alluvial aquifer upstream of the Sheyenne Delta is more poorly defined. In general, the alluvial aquifer system is bounded by the extent of the meander belt, which is bounded by low permeability Cretaceous shales and Pleistocene tills. The meander belt can generally be delineated based upon a noticeable break in topographic slope.

The Sheyenne Delta aquifer may receive small quantities of water from the underlying Dakota Sandstone aquifer, which is under artesian pressure, but only through uncontrolled Dakota Sandstone wells, which yield sodium-sulfate water at an unpumped rate of about 10 gpm (Armstrong, 1982; Hopkins, 1996). A clayey till deposit of up to 260 feet thick (Strobel and Radig, 1997) essentially eliminates direct hydraulic connection between the Dakota Sandstone and the overlying Sheyenne Delta aquifer. Highly plastic, dense clays of Lake Agassiz deposits are found at depths of about 100 feet except in the Sheyenne River valley. These clay deposits probably represent the lake-floor sediments of glacial Lake Agassiz. The thickness ranges from 6 to 24 feet and averages 49 feet. They have a very low transmissivity and function as lower confining beds in the groundwater flow system (Downey and Paulson, 1974). Likewise, the alluvial aquifer may receive underflow via leakage from deeper aquifers but the amount of this leakage is unknown.

The Sheyenne Delta aquifer contains an estimated 4 million acre-feet of groundwater in storage and receives about 50,000 acre-feet of recharge during a year of average precipitation (Baker and Paulson, 1974). The area receives about 20 inches of precipitation annually, of which about three fourths occurs during the May through October growing season. Somewhat more than 82 percent of the annual evaporation (about 30 inches) also occurs during the same period (Armstrong, 1981).

The water table is usually lowest in late winter, just before the spring thaw. During spring thaw, there is usually a sharp rise in the water table and the yearly high often occurs within a month or two after the yearly low, changing from 5 to 10 feet below ground surface to 1 to 5 feet below ground surface during April. Following the high in spring or early summer, the water levels generally decline through the summer, fall, and winter. However, unusually large amounts of precipitation in the summer or fall will cause a lessening in the rate of decline or may even produce slight rises in water levels. The water table elevations change little during frozen winter months (Strobel and Radig, 1997). Winter precipitation has little or no immediate effect because the frost in the ground impedes the infiltration of water. During the winter, there is little precipitation and what precipitation that does fall is mainly in the form of snow (Baker and Paulson, 1974).

Natural surface drainage in the Lake Agassiz Plain is nearly nonexistent except near the Sheyenne River, which flows through the Sheyenne Delta. Short tributaries to the Sheyenne River have formed, but they only carry runoff for short periods following large storms (Armstrong, 1982). Topography strongly affects the focus of recharge in the aquifer; the largest water level rises in the aquifer are associated with low-relief areas, where rapid infiltration of snowmelt, runoff, and precipitation can take place. Snowmelt and precipitation infiltrate into the aquifer in low-relief areas during early spring and produced a rise in water levels. Snowmelt originating in the upland areas accumulates in depressions from surface runoff because of the inability to infiltrate through the frost zone. Ponded water in depressions infiltrates downward to the saturated zone after the frost zone dissipates (Shaver, 1998). Snowmelt and precipitation in high-relief areas, typically in areas near the river, either travel as surface runoff to low-relief areas or to the river or infiltrate to the water table and flow in the direction of the steep hydraulic gradient toward the river. Delayed recharge may be taking place in areas with thicker unsaturated deposits, due to delayed recharge percolation to the water table (Strobel and Radig, 1997).

According to Shaver (1998), summer precipitation events generally are not large enough to overcome soil-moisture deficits and generate recharge. Water that infiltrates the soil must first satisfy field moisture requirements. The excess percolates downward to the saturated zone in which the water moves laterally toward areas of discharge along the River and Delta front, which are at low elevations (Downey and Paulson, 1974). Occasionally during the fall, precipitation exceeds both evapotranspiration and soil-moisture deficits and recharge takes place. Even when recharge does not occur during the fall, soil-moisture deficits generally are reduced, significantly affecting the magnitude of the following spring's recharge event. Depth to the water table is generally less than 8 feet. The capillary fringe of water table and root zone are coupled above this depth. As a result, natural discharge from the Sheyenne Delta aquifer is due, in large part, to evapotranspiration.

Whereas most of the recharge to the aquifer takes place during the spring, the annual average recharge rate over the Sheyenne Delta aquifer was estimated by Armstrong (1981) at 4 to 8 inches, through the calibration of a single-layer digital groundwater flow model.

5.1.2 Discharge from the Aquifer

Of the 6 to 8 inches of normal-year infiltration, 1 to 3 inches reaches the Sheyenne River as baseflow and the remainder is lost to evapotranspiration (Armstrong, 1981). Pumping of groundwater from wells is also a discharge mechanism, although it likely pales in comparison to natural mechanisms (Baker, 1967). The number of application permits to withdraw water from the Sheyenne Delta aquifer for irrigation has increased markedly (Hopkins, 1996). The State Engineer has approved an annual appropriation of 19,123.9 acre-feet from the Sheyenne Delta aquifer. This appropriated volume is 15 percent of the average annual recharge of groundwater in the practical development area of the Delta (Shaver, 1998). Shallow, high-production irrigation wells and crops such as corn and potatoes (that thrive in coarser-grained irrigated soils) are found most commonly on the western part of the Delta (Cowdery and Goff, 1994). The major areas of groundwater discharge are in the

Sheyenne River and its tributaries, the Sheyenne Delta scarp, several manmade drains on the upland surface of the Delta, and where the water table is near land surface, by evapotranspiration (Downey and Paulson, 1974).

The Sheyenne River winds its way eastward through the delta for a distance of about 52 river miles, effectively dividing the aquifer into north and south units. Paulson (1964) had indicated a marked increase in river discharge eastward through most of the aquifer as a result of groundwater inflow. The discharge measurements by Paulson (1964) were limited to the mainstem and did not include tributaries directly. The Sheyenne River is a gaining stream throughout the delta area of Ransom and Richland Counties. The gain in Ransom County was about 14 cfs in the fall of 1963. Precipitation in 1963 was about 90 percent of normal so the measured gain probably was lower than would be expected during a year of normal precipitation (Paulson, 1964).

Low-flow stream measurements were made in May and August 1972 by Downey and Paulson (1974)—most in tributaries. The measurements indicated an increase in river discharge of 109 cfs (cubic feet per second) and 29.4 cfs respectively. The large difference between the two discharge increases is attributed mainly to evaporation, which normally is low in May but near maximum in August. Some of the difference is attributed to steeper hydraulic gradients in May, resulting from recharging spring rains and snowmelt, with consequently higher rates of groundwater movement. Of the 109 cfs increase in discharge measured in May 1972, 17.4 cfs was measured in the tributaries. Of the 29.4 cfs increase in August, 7.6 cfs was in the tributaries. These data indicate that about 84 percent of the discharge measured in May and about 73 percent measured in August was received as seepage inflow through the channel of the Sheyenne River. Furthermore, measurements were made at several points along the lengths of the tributaries and the data showed a fairly uniform increase in discharge, as would be expected in a normal groundwater discharge pattern.

Shaver (1998) indicates that discharge to the Sheyenne River is negligible along the western flank of the aquifer. A "20- to 40-foot difference in water-level elevations between the westernmost irrigation wells and the Sheyenne River...indicates a poor hydraulic connection between the aquifer and the river in this area." In this area, the Sheyenne River is incised into the glacial till.

Discharge of groundwater as springs can take place where the elevation of the ground surface is below the elevation of the water table. In most locations, evapotranspiration keeps the groundwater from "daylighting" but in areas where the topography changes substantially over a short distance (such as in eroded drainages, along the northern scarp of the delta, and in the Sheyenne River valley) springs can form. Many of the springs in the Sheyenne River valley appear to be surface expressions of groundwater at the head of gullies. In some of these gullies, tributaries form. Near the River, fens are present, where the water table is above the ground surface and upwelling conditions are attained. Springs that issue in the Sheyenne River valley or in the tributaries of the Sheyenne River are contributors to the base flow of the river. Discharge of groundwater through numerous springs along the eastern edge of the Delta may be 5 to 10 times as great as the fall and winter discharge to the Sheyenne River. Even so, annual discharge through springs is probably less than half of the estimated annual recharge (Baker and Paulson, 1967).

It is important to note that flow rates of springs issuing above the surface elevation of the Sheyenne River are independent of the elevation of the River. This includes seepage faces that develop in the riverbank.

The average annual maximum potential evaporation rate in an area that includes the Sheyenne Delta aquifer is about 30 inches (Armstrong, 1981). A range of values for maximum evapotranspiration from 25 to 35 inches per year was found by Armstrong (1981) to be in balance with the range of recharge rates (about 20 inches per year) that he used in his model. Maximum depths of 6 to 10 feet for the effective evapotranspiration proved to fit best with observed steady-state conditions. Others, modeling settings similar to the Delta in North Dakota, came up with recharge ranges of between 7 and 8.25 inches per year and effective evapotranspiration depth limits of 8 feet. Shaver (1998) indicates that within about 2 to 3 miles of the Sheyenne River in northern Ransom and Richland counties, the hydraulic gradient of the aquifer is about 20 to 60 feet per mile (0.0038 to 0.0114). In these areas, depths to water table commonly are greater than 8 feet and the capillary fringe of the water table and root zone are uncoupled. The average depth limit of evapotranspiration in the Armstrong (1981) model was set at 8 feet. Recharge was set at 7.4 inches per year, giving the best fit of simulated to measured water levels during calibration, using the assumed values of evapotranspiration (Armstrong, 1981).

Soil developed on the aquifer is porous and permeable. Armstrong (1981) cites a vertical permeability equivalent to infiltration rates of 2 to 6.3 inches per hour in soils similar to those in the Delta. These rates are sufficiently high to preclude most runoff except when the ground is frozen, during extremely intense precipitation periods, or when the water table is very close to the land surface.

5.1.3 Bank Storage

Bank storage refers to the process in which there is a temporary reversal of hydraulic gradient and groundwater flow direction immediately adjacent to a rising river, causing water from the river to flow into the aquifer, rather than from the aquifer into the river. This is a short-term process that typically takes place during spring thaw or during rainfall events that cause a river stage to rise. Once the river stage begins to drop, normal groundwater flow directions are approached and the river water that was stored in the riverbank is discharged back into the river. Thus, it is a process of both recharge to the aquifer and discharge from the aquifer.

Under most conditions and in most locations, groundwater discharges into the Sheyenne River. During flood conditions, the river rises above the adjacent groundwater and flow is reversed from the river and into the aquifer. Aquifer storage is filled and the aquifer and the river slowly work to reach a new equilibrium (the time required to reach this equilibrium is measured by the aquifer's specific yield, which is an unconfined storage coefficient). For unconfined (water table) aquifers, it typically takes much longer for a new equilibrium (steady-state condition) to be reached than the period of time that the river stage is abnormally high (even in the spring). "Stagnation points" develop in the aquifer on either side of the river channel, which represent low points in the water-table surface. On the river-side of the stagnation point, water flows from the river and into the aquifer. On the aquifer-side of the stagnation point, groundwater flow remains toward the river, although flow rates are lowered in response to a lower hydraulic gradient.

When the river stage begins to drop, hydraulic gradients begin to shift once again toward the river and river water that had flowed into the aquifer now flows back into the river. In other words, the "stored" water in the river "bank" is released back into the river.

Strobel and Radig (1997) observed temporal reversals of flow in some locations near the Sheyenne River during spring runoff, which they attributed to bank storage effects. These reversals were not long-lived, lasting only a few weeks.

5.1.4 Aquifer Hydraulic Conductivity

Hydraulic conductivity (similar to permeability) is a measure of a material's ability to transmit water under a hydraulic gradient. It is probably the single most important parameter controlling groundwater flow and was included in a fundamental empirical equation derived by d'Arcy and which bears the name Darcy's Law:

$$q = K \times ?h/?L$$

where: K is the hydraulic conductivity, with units of length per time;

?h is the change in hydraulic head (water level) per length (?L); and

q is the volumetric flow rate per unit area of material with units of length per time

Hydraulic conductivity can be measured through various types of tests, such as slug tests and permeameter tests. It can also be calculated from pumping (aquifer) tests and estimated from grain-size analyses (such as Hazen's method). In general, the coarser the material, the higher the hydraulic conductivity. A clay has a much lower hydraulic conductivity value than does a sand and a gravel has a very high value of hydraulic conductivity.

Transmissivity is also a measure of an aquifer material's ability to transmit water but it generally applies to the aquifer's entire thickness rather than a unit volume or unit area. Transmissivity is typically measured through pumping tests, where water levels in an aquifer are monitored and analytical methods are used to calcula ted transmissivity. Hydraulic conductivity and transmissivity are related through the following equation:

$$T = K \times b$$

where: K is the hydraulic conductivity, with units of length per time;

b is the aquifer's saturated thickness, with units of length; and

T is the transmissivity, with units of length-squared per time.

Obviously, if transmissivity is measured/calculated and the aquifer's saturated thickness is known, the hydraulic conductivity can be easily estimated.

Progradation of the Delta into Lake Agassiz resulted in a general trend of increasing grain size in both the upward and beachward directions. Hydraulic conductivity in the Sheyenne Delta aquifer decreases from the southwest to the northeast as the deposits grade from predominantly sand in the southwest to predominantly silt and clay in the northeast, with a corresponding decrease in hydraulic conductivity. The sand is primarily very fine to fine grained and grades northeastward into silt and clay through a transition zone of interbedded sand and silt (Downey and Paulson, 1974). This trend is consistent with the grain-size distribution expected in a delta that was formed from a river discharging into glacial Lake Agassiz from the southwest. Downey and Paulson (1974) conducted aquifer tests at 3 locations on the Delta, measured hydraulic conductivity in 25 core samples, and applied a water-table profile-analysis method at various locations to produce a map of hydraulic conductivities for the aquifer. This map was digitized and geostatistically analyzed for the purpose of this study.

In Richland County, the delta deposits can be divided into three units: (1) a lower unit of silt interbedded with clay and sand, which is thickest near the eastern margin of the Delta and thins westward; (2) an upper unit of well-sorted sand, which is thickest in the west and thins eastward; and (3) a thin layer of wind-blown sand, which covers the entire Delta. The lower silty unit is more than 150 feet thick at the eastern edge of the delta, less than 50 feet thick near the Richland-Ransom County boundary, and is entirely absent near the western edge of the delta in Ransom County (Baker and Paulson, 1967).

The upper unit of well-sorted sand is as much as 100 feet thick near the Richland-Ransom County boundary, and is entirely absent near the eastern edge of the Delta in Ransom County. Its average thickness in Richland County is about 60 feet. The grain size of the sand generally decreases eastward from medium and coarse along the Richland Ransom County boundary to very fine in the eastern part of the Delta near Walcott (Baker and Paulson, 1967).

The thin layer of wind-blown sand, which covers the entire Delta, is generally less than 10 feet but may be as much as 50 feet in the highest dunes. The upper unit of well-sorted deltaic sand and the overlying deposits of wind-blown sand form the main part of the Sheyenne Delta aquifer—the lower silt unit is generally too fine grained to yield water to wells (Baker and Paulson, 1967).

Transmissivities in the Sheyenne Delta aquifer range from about 200 feet squared per day (1,500 gallons per day per foot) in the silt/clay facies to about 1,400 feet squared per day (10,500 gallons per day per foot) in the sand facies (Downey and Paulson, 1974). Estimates of transmissivity from grain size (5 locations) resulted in 30,000 gpd/ft (gallons per day per foot) near the Richland-Ransom County boundary where the upper sand unit is more than 100 feet thick to less than 500 gpd/ft in the southeastern part of the delta where the upper unit is absent (Baker and Paulson, 1967). The deposits range in thickness from 49 to 140 feet and average 97 feet. The entire Delta thins to the west as the Lake Agassiz basin approaches the surface.

The deltaic deposits in the Sheyenne River valley have been reworked by the meandering, erosive nature of the river. Locally derived sand and gravel from the delta has been mixed with finer grained materials transported by the river from till-dominated areas upstream of the Delta. Downey and Paulson (1974) developed several cross sections perpendicular to the Sheyenne River and concluded that the deltaic deposits have been completely reworked in the Sheyenne River valley throughout its course in the Delta. Downey and Paulson (1974) consider the reworked valley deposits to be hydraulically part of the Sheyenne Delta aquifer but they represent a zone of somewhat lower hydraulic conductivity.

Armstrong (1982) noted that yields form individual wells should range from a few gallons per minute near the western edge and the alluvial areas to about 1,000 gpm in areas where more than 35 feet of gravelly sand exists. Variations in yield within short distances may be large, as discovered by a few prospective irrigators who have drilled two to five test holes in the same quarter section before finding a sufficient thickness to yield enough water to supply a pivot system. However, most of the area will yield more than 250 gpm. The yield range for most of the Sheyenne Delta aquifer is 250 to 1,000 gpm because variations in thickness and transmissivity make closer estimates impractical.

Shaver (1998) indicated that specific capacity tests were conducted by drilling contractors on 23 irrigation wells located in an application evaluation area (test duration ranged from 1 to 100 hours). Transmissivity was estimated using the method of Walton (1970). Estimated transmissivities ranged from 1,700 ft^2/day to about 12,000 ft^2/day, with a mean of 5,400 ft^2/day.

Values of hydraulic conductivity in the narrow alluvial aquifers that border the Sheyenne River upstream of the Delta are not available for site-specific locations. County-scale geologic and hydrogeologic water atlases provide a general indication of the type of clastic alluvial deposits that may be present; however the heterogeneous nature of meander-belt deposits makes prediction of typical hydraulic conductivity values relatively uncertain. In this study, we evaluated the sedimentological descriptions reported in the well logs for the wells at the four cross sections and made estimates of hydraulic conductivity. These values were varied during an ad hoc calibration process (described in a subsequent section). However, it needs to be stated that the estimates of hydraulic conductivity used in this analysis have substantial uncertainty due to the absence of site-specific data.

5.1.5 Aquifer Base Elevation

The Sheyenne Delta aquifer is unconfined (i.e. the piezometric surface and the water table are the same). The saturated thickness of the aquifer is therefore a function of the water-table elevation and the base elevation of the aquifer at any given location. The Sheyenne Delta aquifer has a reported mean saturated thickness of 41 feet in Ransom and Sargent Counties (Armstrong, 1982).

Pleistocene lacustrine clays about 100 feet thick underlie the Sheyenne Delta aquifer throughout (Downey and Paulson, 1974). The clays, which are plastic and have low hydraulic conductivity, form a relatively impermeable basal unit to the aquifer. The contact between the aquifer and the lacustrine clays is poorly defined because the prograding delta deposited over its own bottomset beds, which have essentially the same composition as the lacustrine clays (Baker, 1967). The transmissive delta deposits range in thickness from 49 to 140 feet and average 97 feet, with the entire delta thinning to the west as the Lake Agassiz basin approaches the surface (Downey and Paulson, 1974).

None of the previous studies has a map or other quantitative description of the base elevation of the Sheyenne Delta aquifer. Downey and Paulson (1974) and Armstrong (1981) used transmissivity, rather than hydraulic conductivity, in their digital modeling and therefore did not need to compute base elevation or saturated thickness. However, Downey and Paulson (1974) did make an attempt to delineate the contact between Lake Agassiz lacustrine deposits and deltaic deposits, though they failed to differentiate between the low-transmissive basal deltaic deposits and the highly transmissive deltaic sands.

A map was developed in the Barr (1999) study of the base elevation of the transmissive portion of the Sheyenne Delta aquifer from three sources: selected boring logs in Baker (1967); Plate 2 of Downey and Paulson (1974); and selected borings logs in Armstrong (1979). A Surfer® grid of the base elevation data was made, from which elevations along the model profiles were interpolated. The map of the base elevation of the Sheyenne Delta aquifer is on Figure 8 of the Barr (1999) report.

The base elevation of the Sheyenne Delta aquifer generally slopes from southwest to northeast, following the lacustrine clay surface of the Lake Agassiz deposits. The elevation changes from over 310 meters (1,017 feet, MSL) southeast of Lisbon to about 260 meters (853 feet, MSL) southwest of Kindred; a distance of about 30,000 meters. While not as flat as the overall ground surface topography (excluding local depressions and dunes), the aquifer base does not appear to have much relief. This is consistent with the depositional environment in which the deltaic sands were deposited.

The base elevation of the alluvial aquifer at the four cross sections located outside of the Sheyenne Delta were estimated from the County water atlas data and are general approximations. None of the well logs indicated that the bottom of the well had encountered the bottom of the meander belt deposits – thus, estimations of base elevation could not be interpreted from them.

5.1.6 Groundwater Flow Direction and Water-Level Fluctuations

Regional groundwater flow is from upland areas to the River, at both high and low flood/recharge conditions. The steepest hydraulic gradients are beneath the bluffs on each side of the river valley. Within about two to three miles of the Sheyenne River in northern Ransom and Richland counties, the hydraulic gradient of the aquifer is about 20 to 60 feet per mile (0.0038 to 0.0114) (Shaver, 1998). Two to five miles beyond the river valley, regional gradients become low and local gradients, which are toward individual low areas where evapotranspiration is greatest, mask regional trends (Armstrong, 1982). The Sheyenne River is eroded as much as 120 feet below the surface of deposition of the deltaic sediments. Accordingly, the water table slopes toward the Sheyenne River valley and toward the Delta edges (Baker, 1967). Because a surface-water divide and a groundwater drainage divide are near the Sheyenne River along the western edge of the Delta, only a relatively small amount of groundwater drains westward to the River (Paulson, 1964; Shaver, 1998).

Reversals of groundwater flow very near the River were inferred from water-level data during high stage conditions in the River (i.e. bank storage) by Strobel and Radig (1997). These reversals were "temporary" (less than one month) in duration and very localized near the river (less than one mile from River). Overall hydraulic gradients to the Sheyenne River decreased slightly during this period, due both to higher river stage and to increased infiltration over the aquifer. There is evidence of "ridges" of high groundwater levels bordering both sides of the Sheyenne River valley. These ridges appear to be related lithologic changes in the aquifer and residuals from previous periods of recharge (Downey and Paulson, 1974).

Strobel and Radig (1997) estimate that high stage levels on the Sheyenne River in July and August 1993 probably caused water-table gradients near the River to reverse and water from the River flowed into the aquifer as temporary bank storage.

> "Direct effects of the 1993 flood on water levels in the aquifer probably were limited to the area adjacent to the river… However, excessive precipitation associated with the flood probably affected water levels throughout the aquifer. Water levels in two observation wells in the aquifer indicate that the water table generally was about 2 feet higher during the fall and winter of 1994 than during the fall and winter of 1993" (Strobel and Radig, 1997, p. 35).

The water table fluctuates considerably but most of the time and in most places it is less than 10 feet below the surface. The water table usually is lowest in late winter, just before the spring thaw. During spring thaw there is usually a sharp rise in the water table and the yearly high often occurs within a month or two after the yearly low, changing from 5 to 10 feet below ground surface to 1 to 5 feet below ground surface during April. Following the high in spring or early summer, the water levels generally decline through the summer, fall, and winter. However, unusually large amounts of precipitation in the summer or fall will cause a lessening in the rate of decline or may even produce slight rises in water levels (Baker, 1967). The water-table elevations change little during frozen winter months (Strobel and Radig, 1997). Water-level fluctuations caused by irrigation withdrawals are masked by water-level fluctuations caused by natural variations in recharge and discharge (primarily evapotranspiration) as dictated by changing patterns of climate (Shaver, 1998).

Groundwater divides were delineated by Paulson (1964) in areas of nearly flat hydraulic gradient north and south of the Sheyenne River. These boundaries roughly parallel the Sheyenne River and became boundaries for the finite-difference flow models developed for the studies of Downey and Paulson (1974) and Armstrong (1981). The divides and flow paths (interpreted by Paulson, 1964) are shown on Figure 9 of the Barr (1999) report.

5.1.7 Aquifer Storage Parameters

Aquifer storage parameters are only important when transient (non-steady state) effects are considered. For an unconfined aquifer, the specific yield (Sy) is the storage parameter of importance. As a rule of thumb, the larger the specific yield, the longer it takes for an aquifer stress (such as an increase in the stage elevation of a river) to manifest itself as a change in water level in a hydraulically-connected aquifer. This is because higher specific yield values indicate a larger effective porosity that must be filled by the water as the phreatic surface rises. For unconfined medium-sand aquifers, a typical range for specific yield is 0.16 to 0.46 (mean of 0.32) and for unconfined gravel aquifers a typical range is 0.17 to 0.44 (mean 0.24) (Morris and Johnson, 1967).

Porosity of cores of deltaic sand deposits that were examined by Baker and Paulson (1967) ranged from 40 to 48 percent and averaged 43 percent. Specific yield of four cores ranged from 25 to 40 percent (Baker and Paulson, 1967 noted that these values seemed "rather high" for deltaic sand deposits as a whole but may be representative for the coarser facies). They estimated the specific yield for the upper part of the deposits by comparing the rise in water levels in observation wells with precipitation. An average rise of 3.4 feet in 22 wells was attributed to April rains and to a lesser extent by snowmelt. The average storage for the upper deposits was estimated to be no greater than 10 percent, but that this value was too low to be representative of the entire deltaic strata.

Armstrong (1982) estimates the specific yield (by unknown means and from unknown data) at 0.15. William M. Schuh, Hydrologist Manger, NDSWC summarized storativity calculations for Hecla, Hamar, and Ulen soils (5 sites) in the Oakes aquifer study area in Dickey-Sargent counties (December 31, 1990 memo cited by Shaver, 1998). Specific yield was calculated from total porosity, laboratory wetted porosity, and fielded wetted porosity. Results of this study indicated little difference in specific yield between the zone of pedogenesis and the underlying coarse parent materials. Mean values of specific yield by layer were close to 0.25. Based on this, Shaver (1998) estimated a specific yield for Sheyenne Delta aquifer at 0.25.

Only one pumping test performed in the Sheyenne Delta aquifer has produced a specific yield value that was believed by Downey and Paulson (1974) to be valid (17% or 0.17)—the others were much too low because of incomplete drainage. Downey and Paulson (1974) and Armstrong (1981) rounded this value up to 0.20. Specific yield values from properly conducted pumping tests of sufficient duration to extend past the gravity-drainage period are the most reliable values for unconfined aquifers.

5.2 Analysis Methods

This section describes how the information and data summarized in the conceptual hydrogeologic model were used to make quantitative predictions of the effects of the Devils Lake Outlet project on groundwater in the Sheyenne Delta aquifer and alluvial aquifers.

5.2.1 Hydraulic Effects

Hydraulic effects of the two projects on groundwater levels were analyzed by developing numerical profile models along two non-linear cross sections through the Sheyenne Delta aquifer and four linear cross sections at various locations outside of the Delta (at Sheyenne, Cooperstown, Kathryn, and Walcott) using the U.S. Geological Survey's finite-difference groundwater flow code MODFLOW (McDonald and Harbaugh, 1988; Harbaugh and McDonald, 1996). The cross sections are oriented along the best estimate of groundwater flow paths.

The profile-modeling approach was used in the Barr (1999) study. It was also selected for this study over analytical analyses methods because profile modeling was able to account for changes in aquifer characteristics such as hydraulic conductivity and aquifer thickness, as well as spatial changes in topography and evapotranspiration. All of these parameters could be important considerations. The alternative to profile modeling is a full, three-dimensional computer simulation of the aquifer. While certainly a worthwhile endeavor, three-dimensional modeling of the aquifer would be expensive and computationally demanding, whereas profile modeling is relatively quick. The advantage of the profile-modeling approach is that many more simulations (including transient simulations) could be performed with only a small loss in the "realism" of the simulation.

The locations of the six profile sections that were modeled are shown on Figure 2. For the cross sections that are not in the Sheyenne Delta aquifer (i.e. Sheyenne, Cooperstown, Kathryn, and Walcott), the models were extended out beyond the break in topographic slope, which generally defines the contact between the more permeable alluvial or meander belt deposits and the low permeability shales and tills. High-detail LIDAR data, made available to Barr by the USACOE, was used to identify the break in slope. The profile models were extended beyond the break in slope in order to include some portions of the shales and tills in the models.

The two profiles in the Sheyenne Delta that were used in this study (Delta 1 and Delta 2) correspond to cross-sections two and four, respectively, from the Barr (1999) study. These profiles extend from the groundwater divide of Paulson (1964) to the center of the Sheyenne River, which is a hydraulic boundary. Profiles were not constructed to simulate areas north of the river because the flow path north of the river is much shorter, and because the area where orchids grow is south of the River. It is considered reasonable to assume that the groundwater effects on the north side of the river would be similar to those described for the south side of the river. A profile section was not placed between Section 5 and Section 6 because such a section would roughly coincide with the extensive north-flowing drainage. This north-flowing drainage represents a hydraulic boundary condition that would render the groundwater levels in its vicinity insensitive to stage changes in the Sheyenne River.

5.2.1.1 Description of Flow Equations

The three-dimensional groundwater flow equation is:

$$\frac{?}{?x}\left(K_x \frac{?h}{?x}\right) ? \frac{?}{?y}\left(K_y \frac{?h}{?y}\right) ? \frac{?}{?z}\left(K_z \frac{?h}{?z}\right) ? S_z \frac{?h}{?t} ? R$$

The partial derivatives on the left side of the equation simply state that: (1) hydraulic conductivity (K) can be a tensor (i.e. it can vary, depending upon direction X, Y, or Z) and (2) hydraulic head (h) is a second partial derivative of the three principal directions. The left side of the equation equals zero for a steady-state simulation. The right side of the equation represents the water placed into or taken out of storage as a function of time (t). R is a general sink or source term.

For unconfined flow, it is assumed that T = Kh (i.e. transmissivity equals hydraulic conductivity times aquifer thickness). Further, if flow is being calculated along a flow path, then (by definition) there is no component of flow perpendicular to the stream line. If the streamline is assumed to be along X and Y is perpendicular to X, then the equation above simplifies to:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h^2}{\partial x}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h^2}{\partial z}\right) = 2S_y \frac{\partial h}{\partial t} - R$$

Sy is the specific yield. It is this equation in a profile model that is solved numerically. In the case of MODFLOW, the differential equation is solved by a finite-difference approximation.

5.2.1.2 MODFLOW Profile Model

Each of the six profile models (one for each section) consists of 1 cell wide (width of 20 feet, perpendicular to the flow direction). The number of cells along the profile varies but in general, are about 15 to 20 feet long – much smaller near the river.

With one exception, the models are single layer with the layer being unconfined. This approach is different to the eight layer profile model used in the Barr (1999) study. That study employed eight layers because, prior to obtaining results, the amount of vertical interaction between the water table and deeper portions of the aquifer were not known. The results of the Barr (1999) study demonstrated that there was very little in the way of vertical hydraulic gradients generated. Therefore, this study used only one layer and achieved very satisfactory results with less computational demands.

The profile model for the Delta 2 cross section began as a single layer but a second, lower layer was added to simulate a portion of the lacustrine clays. This change was made because the Sheyenne River is incised below the base of the deltaic deposits in this location. Adding the layer, provided greater continuity of flow and hence, greater computation stability.

The profile model orientation used in this study is termed a "slice" orientation because it is a vertical slice along a flow path. With the slice orientation, no adjustment to hydraulic conductivity, specific yield, or recharge is needed to compensate for the slicing of the aquifer into a section (Anderson and Woessner, 1992). The "moving boundary" problem of a varying water table is not at issue either since the layers are defined as unconfined. Recharge is applied to the top of the layer. The MODFLOW grid was designed and the parameters were entered into the model using the integrated modeling environment Groundwater Vistas.

5.2.1.3 Initial Conditions

The simulations used in this study are termed "transient" simulations because they compute groundwater flow conditions (discharge, water table elevation, etc.) through time in a series of time increments (stress periods and time steps). If the initial flow condition is unstable, changes in water levels during the forward, predictive simulations could be primarily the result of the model attempting to reach an equilibrium, rather than responding to the stage changes of the river. Therefore, an initial condition for each profile model needed to be developed that represented some semblance of stability.

The initial condition was achieved primarily through adjustments to recharge in a steady-state model. In the steady-state model, the stage level of the stream was kept constant (typically at the starting value of the HEC-5-predicted stages) and various recharge values were used in the model until the head in the aquifer was stabilized at a value thought to be representative of natural conditions (for example, the steady-state water table surface could not be above ground surface). The resulting recharge value (an average daily value) was then used to adjust recharge values throughout the year for the transient simulations. In general, the resulting steady-state water levels in the model were in the range of values measured in the monitoring wells (for those sections where wells were available). However, because the wells were located near the river, there were no well data to compare the far-field heads. Generally, however, the far field heads are not of interest in this study as they are not likely affected by stage levels of the river.

5.2.1.4 Ad Hoc Calibration

The profile models are not conducive to rigorous calibration methods typical of three-dimensional groundwater flow modeling. For the profile models representing conditions near Cooperstown, Kathryn, and Walcott, the water level data for the monitoring wells overlapped with discharge data at the nearest gage (the overlap was not available for Sheyenne). Calibration simulations of 1-year in length were performed in which the stage elevation of the stream was varied daily in the Variable Constant Head package (CHD) in MODFLOW. The resulting simulated water levels at the wells were compared to the water levels measured in the wells. For many wells, the simulated and observed water levels were in good agreement. Adjustments to hydraulic conductivity and specific yield were made so that a better match could be achieved for those wells that did not agree as well. Typically, the changes were small and in the end, the specific yield value used was 0.15 for all of the profile models. In some cases, the boundary between the shale/till and the more permeable alluvium could be inferred on the basis of the response of the wells to stage changes.

The monitoring well data included several data points for each day but the simulations in the calibration used stress periods of one full day, primarily because the stage data for the river was in one-day increments. A procedure was developed to calculate the average water level for a given day to be used in the calibration process.

It should be noted here that during the calibration process, it became obvious that at some cross section locations, the stage data from the nearby gage was clearly not appropriate for the cross section, either because the rating curve was not applicable or, more likely, because of the gradient of the river. In order to get better agreement between measured water levels in wells and river stage, the stage data required interpolation between gages. A linear interpolation method was used (a similar method was employed in the Barr (1999) study). This generally provided good agreement between stage levels and the water levels in monitoring wells close to the river. However, this is a source of uncertainty in the models' predictions.

5.2.1.5 Transient Analysis

The annual river stage rise and groundwater level rise share a common cause: spring thaw releasing water trapped as snow and frost and somewhat higher-than average precipitation in April and May (Baker and Paulson, 1967; Strobel and Radig, 1997). In other words, groundwater levels rise naturally in the spring and these rises are generally not because the stage level of the Sheyenne River is rising (Strobel and Radig, 1997) – particularly in areas not immediately adjacent to the river.

In order to determine the effects of the proposed projects on a typical spring cycle, it was necessary to simulate the superposition of elevated river stage (above and beyond the typical effects) on the typical spring cycle and determine the effects in terms of deviations from the typical condition. As such, this is a transient (time-dependent) problem. The question is: how much additional change in groundwater level is predicted to result from the additional increase in river stage?

5.3 Data and Assumptions Used in MODFLOW Analyses

The sources of hydrogeologic data were described in Section 5.1. Ranges of reported values for water budget factors and aquifer parameters are summarized in Table 1. Values used in the modeling are discussed below, along with additional details. Data specific to each project are discussed in the following subsections.

5.3.1 Hydraulic Conductivity, Aquifer Base Elevation, and Specific Yield

Hydraulic conductivity values for the Sheyenne Delta aquifer were based on Plate 3 of Downey and Paulson (1974). As described previously, a digital Surfer® map was constructed from these data and is shown on Figure 7 of the Barr (1999) report. Aquifer base elevation varied across the site and was gleaned from various sources, as described in Section 5.1. The grid values that result from the geostatistical routines that went into making Figures 7 and 8 became the basis for assigning parameters to profile models.

The specific yield value used in all simulations was 0.15, which is slightly lower than the 0.2 value used by Downey and Paulson (1974). This is considered a conservative value.

5.3.2 Recharge

The initial estimates for typical monthly precipitation values were acquired from the Northern Prairie Wildlife Research Center via the Internet at:

http://www.npwrc.usgs.gov/resource/othrdata/climate.

The data are included in Appendix C. Since several previous studies (e.g., Downey and Paulson, 1974; Armstrong, 1982; Strobel and Radig, 1997) indicate that most of the recharge takes place immediately following frost-out and during the spring months precipitation falling in December through February were not applied until March to simulate the effects of frost preventing infiltration.

In the calibration process, previously described, the monthly averages of precipitation were scaled in order to better represent the model's flow budget; however the relative magnitudes of precipitation from month to month were retained.

5.3.3 Surface Topography

The topography of the ground surface is generally not a parameter in most groundwater models but it was used in this model as a control on spring formation (i.e. where groundwater elevations are higher than the ground surface) and evapotranspiration (which is a function of depth to groundwater at a given location).

Ground surface elevation for the cross sectional models of the Sheyenne delta was obtained from digital elevation maps (DEMs) developed by the U.S. Geological Survey and downloaded from the Internet at http://www.gis.swc.state.nd.us/. These DEMs were converted to UTM NAD 27 coordinates and incorporated into an ArcView® GIS project. Elevations in feet above mean sea level were then obtained for each MODFLOW profile model cell along each section. Spot checks were performed with U.S. Geological Survey 7.5 minute quadrangle maps in the immediate vicinity of where the profile and the Sheyenne River intersected. The accuracy of the elevation data was considered sufficient for the intended use because the modeling was intended to reflect the relatively large vertical difference between the upland areas and the river (a difference of up to 120 feet, Strobel and Radig, 1997, p.7).

For the cross sections at Sheyenne, Cooperstown, Kathryn, and Walcott, detailed LIDAR data with an accuracy of one foot was used.

5.3.4 Evapotranspiration

The Evapotranspiration Package in MODFLOW was employed in simulating the Devils Lake Outlet stage effects. Two parameters are required: (1) the maximum evapotranspiration potential and (2) the depth below which maximum evaporation no longer takes place. The ground surface elevation must also be known— this is described in the previous section.

The Evapotranspiration Package assumes an evapotranspiration removal rate equal to the maximum evapotranspiration potential between the ground surface and the depth at which the maximum no longer holds. This value was taken from Downey and Paulson (1974) as 7.16 feet. The depth at which evapotranspiration from the water table ceases was also taken from Downey and Paulson (1974) at 11.25 feet. From 7.16 feet downward to 11.25 feet, the evapotranspiration rate decreases linearly.

5.3.5 Sheyenne River Stage

The USACOE provide HEC-5 modeled flow data for gaged locations along the Sheyenne River for a period of 50 years on a daily basis, assuming (1) climatological conditions similar to the past 50 years and (2) climatological conditions similar to the past 50 years with the addition of the 300 cfs discharge conditions from Devils Lake. These two sets of data became the basis for estimating stage data in the models.

Stage-elevation curves for the various gages were obtained and polynomial rating curves were calculated. Using the site-specific rating curve, the modeled flow data (in cfs) was transformed into stage data (feet above mean sea level). The river stages were interpolated between two gages to a cross section location assuming a linear relationship with river mile.

A period of 50 years on a daily basis is simply too much data to use in a transient groundwater simulation. The stage data was reviewed and it was quickly determined that there were no obvious periods of abnormally high stage. Therefore, the first 10-year period was selected out of the 50-year record to perform the MODFLOW simulations. This period was deemed to be typical and representative of the remaining 40 years of modeled record.

5.3.6 MODFLOW Simulation Criteria

Simulation convergence criteria was generally set at 1×10^{-3} feet for the maximum head change between iterations and 0.01 ft^3/day for the maximum flux change for any cell between iterations. Stress periods of one day, with one time step were used. Simulations were 730 days (2 years) in duration. The final heads from one simulation period were used as the starting heads for the next 2 year simulation and the process was repeated until 10 years of simulation were completed. For each two-year simulation period, a new set of stage data were imported into the model. The recharge and evapotranspiration conditions changed monthly and repeated themselves each year – i.e. no unusually wet or dry conditions were modeled in the recharge.

The BCF2 Block-Centered Flow package was employed in the simulations. The PCG2 conjugate block solver was used.

5.4 MODFLOW Simulation Results

This section describes the results of the MODFLOW simulations for the profile models through the Sheyenne Delta aquifer and alluvial aquifer. Because the simulations are transient, the water level in the aquifer may be different, depending on the particular time step and stress period. The primary focus of this study is the maximum increase in the water level due to the particular project.

Transient groundwater simulations produce huge volumes of results. For example, a 10-year simulation produces 3650 water-level data points for each grid cell – there are hundreds of grid cells for each profile. Additionally, for each profile, there are two conditions to be evaluated – 10 years of data for “base” conditions (i.e., no discharge from Devils Lake) and 10 years of data with the 300 cfs release from Devils Lake. We have attempted to distill from these simulation data sets, the key pieces of information that the reader can use to assist in drawing conclusions. We have portrayed the data in terms of (1) hydrographs for key locations on a cross-sectional profile (i.e., water level elevation as a function of time and with respect to ground surface) and (2) profiles of average, maximum, and minimum water level through the cross section and with respect to ground surface elevation. These plots are in Appendix E. They represent the key portrayal of the modeling results.

In describing the change in water level, a value of 0.5 feet is used as the demarcation between significant and insignificant differences due to the discharge from Devils Lake. The primary reason for selecting a cutoff that is above zero is a recognition of the inherent uncertainty in predicting changes at this small level.

5.4.1 Water Levels at Sheyenne

Increases in the average and maximum water levels at Sheyenne due to the Devils Lake project are below 0.5 feet at a distance of 250 feet from the river bank (Figure 7). At distances beyond 250 feet the fluctuations in groundwater levels are virtually indistinguishable from one another. Even 500 feet south of the river, the dominant response to water levels appears to be due to the monthly fluctuations in recharge.

Some of the plots (e.g., 500S and 800S) show an overall trend of increasing water levels, with seasonal fluctuations superimposed upon this trend. This trend should be disregarded as it is a manifestation of a slight overestimation in the average annual infiltration. This trend has nothing to due with differences between river stage elevation with and without the Devils Lake discharge.

5.4.2 Water Levels at Cooperstown

The MODFLOW profile modeling results indicate that the effects of increased groundwater levels due to the Devils Lake discharge are less than 0.5 feet within about 550 feet of the river bank at Cooperstown (Figure 8). However, even at a distance of 1,600 feet from the river bank, the dominant source of fluctuating water levels appears to be the changes in river stage, rather than monthly fluctuations in recharge. The relatively small difference in groundwater levels and between the two flow conditions is due to the relatively small difference in river stage at Cooperstown.

5.4.3 Water Levels at Kathryn

The MODFLOW modeling results for the Kathryn profile indicate that the 0.5 foot difference resulting from the discharge at Devils Lake is at 150 feet from the river bank (Figure 9).

On the west side of the river, there is a slight upward trend during the 10-year simulation period, most evident at distances of about 300 feet from the river bank. As with Sheyenne, this is not due to the Devils Lake discharge but is due instead, to the shales on the west bank which cannot accommodate the estimated recharge and are reaching a new equilibrium during the simulation. This tend is due to the slight errors in estimating the recharge and not due to the Devils Lake discharge.

5.4.4 Water Levels at the Sheyenne Delta 1 Section

The difference in average and maximum water levels between the two modeled conditions is less than 0.5 feet within 100 feet of the river bank at Delta 1 in the Sheyenne delta aquifer (Figure 10). Small responses to water level changes can be seen over 2000 feet away from the river bank but there is no difference in this response between the stage condition with the Devils Lake discharge and the stage condition without it.

5.4.5 Water Levels at the Sheyenne Delta 2 Section

At Sheyenne Delta Section 2, the 0.5 foot difference for average conditions is at about 50 feet from the river bank (Figure 11). The hydrograph for the location 2,000 feet from the river bank shows almost no response to water level fluctuations but the maximum difference between the base condition and 300 cfs condition was at about 2,000 feet from the river bank (Figure 11).

5.4.6 Water Levels at Walcott

Maximum and average groundwater level changes are less than 0.5 feet at a distance of about 300 feet from the river bank at the Walcott section (Figure 12). The Walcott simulations were performed without recharge, which allowed the effect of the increased stage to manifest itself slightly farther away from the river than at Delta 1 and Delta 2 Sections. The reason recharge was not used at Walcott was to have one simulation that allowed for the examination of the worst case effect of increased stage level. It is likely that the distance from the river bank to the 0.5 foot change would be similar to that of Delta 1 and Delta 2 if recharge were included.

5.4.7 Map of Groundwater Level Increase

The distance from the river to the location where the average and maximum water level difference between the two conditions is 0.5 feet was linearly interpolated between the six cross sections for the Sheyenne River. This results in a very narrow band that parallels the river on both sides. In order to generate a map of this zone, we created a script for ArcView GIS that performs the interpolation by creating a series of overlapping polygons, spaced out from the coordinates of the river, These overlapping polygons were then merged into a single (albeit irregularly shaped) polygon. The resulting map is shown on Plate 1. Electronic shape files are provided with this report, which will allow better detail at a smaller scale.

5.5 Modeling of Water-Quality Effects

The Barr (1999) study showed that water from the Sheyenne River can only enter the aquifer if the water level in the River is above the water level in the adjacent aquifer materials. As discussed in this report, that condition can only occur during bank-storage conditions. Once the river stage drops, water in bank storage is released back into the river.

The maximum increases in water levels in the aquifer that were predicted from the MODFLOW simulations are not reflective of the degree of incursion of Sheyenne River water. In fact, the distance of maximum incursion is undoubtedly very much closer to the River than the line that represents the maximum extent of water-level increase. This is because a change in water level in the aquifer is not synonymous with a reversal in hydraulic gradient.

As an extremely (and unrealistic) worse-case condition, one could assume that the line of zero water-level increase corresponds to the maximum distance of incursion of Sheyenne River water. Besides the fact that this is hydraulically impossible, other conditions should be considered, such as reactivity of solutes, sorption, aquifer porosity, etc.

A simple solute transport model was developed for each cross section to examine the distance of incursion of river water into the adjacent aquifer and compare the difference between the two modeled conditions. The transport code MT3D (Zheng, 1992) was used in conjunction with MODFLOW for this purpose. MT3D is a widely used code, developed for the U.S. EPA.

There are a number of constituents in the Sheyenne River water that may be of concern with regard to incursion into the aquifer. Examples include nitrates, chloride, phosphorous, metals, sodium, and sulfate. Sulfate is a good solute to evaluate because it is in relatively high concentrations in the river and concentrations are projected to be somewhat higher with discharge from Devils Lake. Another reason to examine sulfate is that it is relatively non-reactive (i.e. conservative).

As part of the HEC-5 modeling results that the USACOE provided, daily estimates for sulfate both with and without the Devils Lake discharge were included for the various gage locations. We used these daily data to model a 2-year period (years 4-6) of the 10 year MODFLOW simulation period. The sulfate concentrations in the river are typically over 100 ppm (mg/L), which is at a high enough concentration to mask numerical dispersion effects in the solute transport model.

There are many factors that affect solute transport, including sorption, precipitation, degradation, and dispersion/diffusion. Also important is the initial concentration of the solute in the aquifer – a value that can only be guessed at for each cross section. We set this value in the aquifer uniformly at 50 ppm. This value is not very important because the main concerns are the change in concentration due to reversal of flow gradients and the relative difference in effect between conditions with and without the Devils Lake discharge.

Other conditions set in the transport model are: dispersion is zero, sorption is zero, decay is zero, porosity is 0.2, a transport time step of 0.5 days is used, and HMOC is used to minimize numerical dispersion. Plots of the simulation results are in Appendix F.

The transport modeling results demonstrate that the river water incursion is typically only about 25 feet from the river bank. More significantly, after high water periods, bank storage is released and the sulfate is flushed back into the river. The exception to this phenomenon is the Walcott cross section, but this exception is due to the absence of recharge in the model.

The solute transport model results do not show much difference between the condition with the Devils Lake discharge and without it. Nitrate, phosphorous, and chloride can be expected to behave similar to sulfate. Metals and sodium would be much more attenuated (particularly metals) and would not be expected to move as far into the aquifer as sulfate.

6.0 Conclusions

Based on the review of previous studies and the MODFLOW modeling analysis performed for this study, the following conclusions are presented.

1. The maximum water-level increase in the aquifer, resulting from the 300 cfs increased flow in the Sheyenne River is predicted to be between 50 feet (at Sheyenne delta aquifer section Delta 2) and 300 feet (at Walcott). The estimate at Walcott is conservatively high. These values are similar yet slightly smaller than those found in the Barr (1999) study.

2. Excursion of Sheyenne River water during the flood event is about 25 to 50 feet. Sulfate was used as a surrogate to evaluate the incursion. The differences in incursion distance and concentration in the aquifer between the two modeled conditions was found to be minimal.

These conclusions appear to be entirely consistent with observations and analyses made by others during previous studies. The analysis method and selected parameters reflect conditions described in previous studies. For those hydraulic parameters that do not have site-specific values, every attempt was made to use an appropriate value.

This study indicates that the river-stage increases predicted for the proposed projects will not cause changes in groundwater levels beyond the immediate vicinity of the Sheyenne River. Groundwater quality impacts, if any, will be even more restricted the close proximity of the Sheyenne River and will likely not be discernable from current conditions

7.0 References

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Table 1
Estimated Aquifer Parameters and Water Budget Elements

Parameter	Estimated Value	Source and Comments
Water Budget Factors		
Annual recharge to the Sheyenne Delta aquifer	50,000 acre-feet/year (assuming area of 300 mi^2,)	Baker and Paulson, 1967, p. 25
	6 in/year to 8 in/year	Armstrong, 1982, p. 33; based on a digital model of part of the delta area
Portion of recharge discharged to the Sheyenne River	1 in/year to 3 in/year of the total 6 in/year to 8 in/year	
Portion of recharge discharged to evapotranspiration	5 in/year of the total 6 in/year to 8 in/year	
Groundwater discharge from the Sheyenne Delta aquifer to the Sheyenne River	91.6 ft3/sec in May, 1972	Downey and Paulson, 1974, p. 12; lower value measured in August attributed to evaporation from the stream
Groundwater discharge from the Sheyenne Delta aquifer to the Sheyenne River	0.16 ft3/sec per mile of river during October through February for the period 1957-1962	Paulson, 1964, Table 1; use this value in profile model calibration
Total pumpage from the Sheyenne Delta aquifer in Ransom and Sargent Counties	830 acre-feet in 1977	Armstrong, 1982, p. 33
Total pumpage from the Sheyenne Delta aquifer in eastern Ransom County	2000 acre-feet in 1996, applied over 2500 acres	Shaver, 1998, Figure 12
Average irrigation application rate on the Sheyenne Delta aquifer in eastern Ransom County	9.7 inches/acre	Shaver, 1998, p. 10
Total approved appropriation from the Sheyenne Delta aquifer	19,120 acre-feet	Shaver, 1998, p. 13
Potential (maximum) evaporation rate	30 in/year	Meyers, 1962 in Downey and Paulson, 1974, p.15
Annual precipitation	497 mm (19.57 in/yr)	Sieg and Wolken, 1998
Depth of maximum evapotranspiration surface	7.16 feet	Downey and Paulson, 1974, p. 16
Extinction depth for evapotranspiration	8 feet below ground surface	Inferred from discussion on pp. 3-4 of Shaver, 1998
	3.8 feet below the maximum evapotranspiration surface for silty clay; 7 feet below the maximum evapotranspiration surface for silty sand	Downey and Paulson, 1974, p. 16
Aquifer Parameters		
Transmissivity of the Sheyenne Delta aquifer	700 ft2/day, 850 ft2/day, 1000 ft2/day	Downey and Paulson, 1974, p. 8; based on aquifer testing
	6000 ft2/day (saturated thickness 33 feet, K = 180 ft/day)	Shaver, 1998, Table 1; values for tests of 100 hour duration; wells located near western margin of aquifer (coarsest material)
Hydraulic conductivity of various lithologies of the Sheyenne Delta aquifer:		Downey and Paulson, 1974, p. 9; based on laboratory testing
Silty clay	1e-4 ft/day	
Clay, silt, and sand	1e-3 ft/day	
Clayey silt	3e-2 ft/day	
Silt	3e-1 ft/day	

Table 1
Estimated Aquifer Parameters and Water Budget Elements

Parameter	Estimated Value	Source and Comments
Silty sand	1.1 ft/day	
Very fine to fine sand	7.2 ft/day	
Fine sand	16.5 ft/day	
Fine to medium sand	30 ft/day	Downey and Paulson, 1974, p. 9; based on grain size distribution
Medium sand	60 ft/day	
Transmissivity of the sand facies of the Sheyenne Delta aquifer	1400 ft2/day	Downey and Paulson, 1974, p. 9
Transmissivity of the silt-clay facies of the Sheyenne Delta aquifer	200 ft2/day	Downey and Paulson, 1974, p. 9
Hydraulic conductivity distribution for the Sheyenne Delta aquifer	variable	Downey and Paulson, 1974, plate 3
Specific yield of the Sheyenne Delta aquifer	0.2	Downey and Paulson, 1974, p. 14 (used in model, source not indicated)
Specific yield of the coarser units of the Sheyenne Delta aquifer	0.17	Baker and Paulson, 1967, p. 21 based on comparison of lithology to that in which an aquifer test was performed in the Hankinson aquifer (Powell, 1956, p. 20)
Specific yield of soils similar to those developed on the Sheyenne Delta aquifer	0.25	Shaver, 1998, p. 8; based on laboratory and field testing

Strobel, M.L. and S.A. Radig, 1997. Effects of the 1993 flood on water levels and water quality in the Sheyenne Delta aquifer, southeastern North Dakota, 1993-94. USGS Water-Resources Inv. Report 97-4163, 43 p.

Summary

A study was conducted to evaluate the effects of precipitation and flooding on water levels in the Sheyenne Delta aquifer and to evaluate the variations in water quality that are related to the precipitation and flooding. Water-level, streamflow, and water-quality data collected prior to July 1993 were assumed in this study to be representative of pre-flood conditions. Data collected from July 1993 through May 1994 were used to evaluate the groundwater response.

Water levels in 49 wells were measured every three weeks between November 1993 and May 1994. Water samples were collected from 16 wells during November 1993 and March, April, and May 1994 and were analyzed for major ions, nutrients, selected trace elements (arsenic and selenium) and pesticides. The water-level and water-quality data collected during the study, along with similar data collected during the NWQA study provided the basis for describing the general characteristics of the hydrology and water quality of the Sheyenne Delta aquifer.

The study area is a deltaic deposit formed along the margins of glacial Lake Agassiz during the Pleistocene. The Sheyenne Delta aquifer drains to the Sheyenne River. The aquifer underlies parts of Cass, Ransom, and Richland Counties and part of the Sheyenne River Valley and adjacent areas between the cities of Lisbon and Kindred. Land overlying the aquifer consists of about 440 square miles of relatively flat lake plain and gently rolling hills, referred to as low-relief areas in this study. The steep banks and hills are adjacent to the river (high-relief areas) and were produced by surface erosion and eolian dune formation. The land overlying the aquifer is used mainly for cattle grazing and corn and soybean production. Surface drainages (other than the Sheyenne River) are poorly developed because of permeable soils and deltaic deposits. Groundwater flow is generally toward the river or to the east. Discharge from the aquifer is mainly to the Sheyenne River, to springs along the northeast edge of the delta, and (to a lesser extent) to wells and by evapotranspiration.

Streamflow measurements on the Sheyenne River between Valley City and West Fargo (Paulson, 1964; Harkness et al., 1988) indicate that discharge from the Sheyenne Delta aquifer provides substantial baseflow to the Sheyenne River. Measurements made during September through November 1963 showed an increase in streamflow of about 29 cfs between Lisbon and Kindred with no tributary flows (indicates that @ 75% of streamflow at Kindred was from discharge from Sheyenne Delta aquifer (Paulson, 1964)). Measurements made during October 1986 showed an

increase of about 52 cfs between Lisbon and Kindred with no tributary inflows (@ 68% of streamflow at Kindred was from aquifer (Harkness et al., 1988)). Difference in two sets of measurements indicates greater release from the Baldhill Dam upstream from Valley City and a wetter climate pattern during 1986 than during 1963. During the wetter period, more water was discharged from the Sheyenne Delta aquifer to the Sheyenne River but the difference in the ratio of groundwater discharge to total streamflow for the two periods was only 7 percent.

Summary of Geology

The Sheyenne Delta, which generally delineates the Sheyenne Delta aquifer is a Pleistocene, near-surface feature that overlies lacustrine sediments of glacial Lake Agassiz (Baker, 1967a). The delta consists mainly of interbedded fine to medium sand and silt that generally is 49 to 140 feet thick (Downey and Paulson, 1974). The delta is bounded by glacial drift on the west and south and grades into lacustrine sediments in the east and north. The deltaic deposits grade from predominantly sand in the southwest to predominantly silt and clay in the northeast (Downey and Paulson, 1974). The northeastern edge of the delta forms an escarpment and is continuous with sandy deposits of the Campbell beach, one of the lower shorelines of glacial Lake Agassiz (Baker, 1967a). Grain size in the deltaic deposits generally increases in both the upward and shoreward (southwest) directions because of the progradation of the delta into glacial Lake Agassiz (Cowdery and Goff, 1994). In many places, the deltaic deposits have been modified into sand dunes by wind action (Downey and Paulson, 1974).

The low-relief areas of the Sheyenne Delta consist of Ulen-Hecla association soils and, to a lesser degree, Ulen-Stirum association soils (Omodt et al., 1968). In both types of soils, surface drainage is absent and precipitation and snowmelt percolate to the water table. Permeability is moderately high and infiltration is moderately rapid. The high-relief areas of the Sheyenne Delta consists of Valentine-Hecla-Hamar association soils (Omodt et al. 1968). Surface drainage in these soils also is absent and precipitation and snowmelt percolate rapidly to the water table. Permeability is high, infiltration is rapid, and the water-retention capacity is small (Omodt and others, 1968).

Pleistocene lacustrine clays about 100 feet thick underlie the Sheyenne Delta aquifer throughout the study area (Downey and Paulson, 1974). The clays, which are plastic and have low hydraulic conductivity, form a relatively impermeable basal unit to the aquifer. The contact between the aquifer and the lacustrine clays is poorly defined because the prograding delta deposits over its own bottomset beds, which have essentially the same composition as the lacustrine clays (Baker, 1967a).

A thick sequence of Pleistocene-age till and stratified drift underlies the lacustrine clays (Downey and Paulson, 1974). The 81- to 263-foot thick sequence of glacial deposits has low hydraulic conductivity and, along with the lacustrine clays, generally isolates the Sheyenne Delta aquifer from any significant hydrologic interaction with bedrock aquifers. The major water-bearing bedrock unit underlying the Sheyenne Delta aquifer is sandstone in the Cretaceous Dakota Group.

Hydraulic conductivity in the Sheyenne Delta aquifer decreases from the southwest to the northeast (Downey and Paulson, 1974). This trend is consistent with the grain-size distribution expected in a delta that was formed from a river discharging into glacial Lake Agassiz from the southwest. Downey and Paulson (1974) conducted aquifer tests at 3 locations on the delta, measured hydraulic conductivity in 25 core samples, and applied the water-table profile-analysis method (Rorabaugh, 1960) at various locations to produce a map of hydraulic conductivities for the aquifer. Transmissivities range from about 200 feet squared per day in the silt/clay facies to about 1,400 feet squared per day in the sand facies (Downey and Paulson, 1974).

The Sheyenne Delta aquifer is unconfined throughout the study area and is recharged by direct infiltration of snowmelt and rain. Except for the Sheyenne River, surface drainage across the aquifer is minor because of the generally rapid infiltration of snowmelt and rain through the sandy soils into the aquifer. During the study (July 1993 through May 1994), the water level in low-relief areas ranged from above land surface (surface ponding) to 20.5 feet below land surface. The water level in high-relief areas ranged from 3.5 to 24.1 feet below land surface, commonly about twice as deep as in low-relief areas.

The hydraulic findings of this study are as follows:

?? precipitation and flooding affect water levels in the aquifer

?? the largest water level rises in the aquifer are associated with low-relief areas, where rapid infiltration of snowmelt, runoff, and precipitation can take place.

?? topography strongly affects the focus of recharge in the aquifer. Snowmelt and precipitation infiltrate into the aquifer in low-relief areas during early spring and produced a rise in water levels. Snowmelt and precipitation in high-relief areas, typically in areas near the river, either travel as surface runoff to low-relief areas or to the river or infiltrate to the water table and flow in the direction of the steep hydraulic gradient toward the river.

?? the water table elevations change little during frozen winter months

?? delayed recharge may be taking place in areas with thicker unsaturated deposits, due to delayed recharge percolation to the water table.

?? during March, water levels in the aquifer rose by more than 2 feet in some areas as substantial recharge took place over large parts of the aquifer, in response to precipitation and snow melt. Water levels then generally declined during the first half of April as snow melt declined.

?? Excessive precipitation in late April produced higher water levels throughout the aquifer. The streamflow peak resulting from the late April rains occurred quickly than the normal post-snowmelt streamflow recession continued.

?? regional flow is from upland areas to the river, at both high and low flood/recharge conditions. Steepest hydraulic gradients are near the river.

?? reversals of groundwater flow very near the river were inferred from water-level data during high stage conditions in the river (i.e. bank storage). These reversals were "temporary" (less than one month) in duration and very localized near the river (less than one mile from river). Overall hydraulic gradients to the river decreased slightly during this period, due both to higher river stage and to increased infiltration over the aquifer.

?? Authors estimate that high stage levels on the Sheyenne River in July and August 1993 probably caused water-table gradients near the river to reverse and water from the river flowed into the aquifer as temporary bank storage. "Direct effects of the 1993 flood on water levels in the aquifer probably were limited to the area adjacent to the river." "However, excessive precipitation associated with the flood probably affected water levels throughout the aquifer. Water levels in two observation wells in the aquifer indicate that the water table generally was about 2 feet higher during the fall and winter of 1994 than during the fall and winter of 1993." (P. 35).

The water-quality findings of this study are as follows:

?? The aquifer is generally a calcium bicarbonate or calcium magnesium bicarbonate type, with dissolved-solids concentrations ranging from 269 to 1,820 mg/L.

?? "No discernable differences existed between the pre-flood data and the post flood data for both dissolved-solids and chloride concentrations." (P. 35)

?? where major-ion concentrations did change, the change was probably the result of a combination of interaction between the aquifer and the Sheyenne River and recharge from snowmelt.

?? Nitrite plus nitrate concentrations were generally less than 1.0 mg/L as N and no spatial or temporal pattern was apparent.

?? Phosphate concentrations ranged from 0.03 to 1.9 mg/L as P and orthophosphate concentrations ranged from less than 0.01 to 0.32 mg/L as P. The largest concentrations of both constituents was in well SF-1S, located adjacent to the Sheyenne River.

?? large arsenic and selenium concentrations were measured in some samples from the Sheyenne Delta aquifer. Arsenic concentrations ranged from less than 1 to 110 ug/L ad a sample from well SD-22 exceeded the State standard of 50 ug/L. Selenium concentrations ranged from less than 1 to 53 ug/L and one sample from well SD-26 exceeded the State standard of 50 ug/L. Generally arsenic and selenium concentrations were inversely proportional.

?? The only pesticide detected was picloram and it was randomly distributed (reflecting local land use)

Citations used in this Summary:

Baker, C.H., Jr., 1967a. Geology and ground water resources of Richland County, Part 1, Geology: North Dakota Geological Survey Bulletin 46 and North Dakota State Water Commission County Ground Water Studies 7, 45 p.

Cowdery, T.K. and K. Goff, 1994. Nitrogen concentrations near the water table of the Sheyenne Delta aquifer beneath cropland areas, Ransom and Richland Counties, North Dakota: Proceedings of the North Dakota Water Quality Symposium, Fargo, North Dakota, March 30-31, 1994, North Dakota State University Extension Service, p. 89-102.

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Abstract

Water supplies in Richland County are obtained mainly from ground water. The most important sources are the shoreline deposits of glacial Lake Agassiz. These deposits contain two main aquifers—identified as the Sheyenne delta aquifer and the Hankinson aquifer, which have a combined area of about 400 square miles. They consist of well-sorted deposits of sand that are at least 50 feet thick in most places and as much as 100 feet thick near the western boundary of the county. Grain-size analyses indicate possible well yields of at least 50 gallons per minute in most places and as much as 1,000 gallons per minute in a few places. The aquifers are relatively undeveloped and water levels are only a few feet below land surface. The Sheyenne delta aquifer contains an estimated 4 million acre-feet of ground water in storage and receives about 50,000 acre-feet of recharge during a year of average precipitation. The water in the Sheyenne delta and

Hankinson aquifers generally contains less than 500 parts per million dissolved solids, and, although hard, is usable for most purposes.

Aquifers of less importance are associated with the till deposits, and in the bedrock formations, chiefly the Dakota Sandstone. The aquifers in or associated with the till generally are smaller and less productive. Aquifers in the bedrock yield water that is of rather poor chemical quality. However, wells developed in these sources may be capable of yielding 500 gallons per minute in places.

Findings

- Water from the Dakota Sandstone in Richland County is highly mineralized and the TDS is generally more than 2,500 ppm. Most wells produce @ 5 gpm. Largest production is from Wahpeton municipal wells (35-50 gpm).

- Drift aquifers in Richland County: Sheyenne Delta deposits and Lake Agassiz beach deposits. Some water may be obtained from the silt unit that locally composes the upper part of the lake-floor deposits.

- Sheyenne Delta covers about 750 square miles, of which 500 square miles is in northwestern Richland County. The water-bearing portion of the delta in Richland County has an area of about 300 square miles.

- Maximum thickness of delta deposits is 200 feet but the average thickness in Richland County is about 100 feet (Baker, 1966b). In Richland County, the deposits can be divided into three units:

  (1) a lower unit of silt interbedded with clay and sand, which is thickness near the eastern margin of the delta and thins westward;

    a. The lower silty unit is more than 150 feet thick at the eastern edge of the delta, less than 50 feet thick near the Richland-Ransom County boundary, and is entirely absent near the western edge of the delta in Ransom County

  (2) an upper unit of well-sorted sand, which is thickest in the west and thins eastward;

    a. The sand unit is as much as 100 feet thick near the Richland-Ransom County boundary, and is entirely absent near the eastern edge of the delta in Ransom County.

    b. Its average thickness in Richland County is about 60 feet.

    c. The grain size of the sand generally decreases eastward from medium and coarse along the Richland Ransom County boundary to very fine in the eastern part of the delta near Walcott

  (3) a thin layer of wind-blown sand, which covers the entire delta.

a. The thickness of the wind-blown surficial sand is generally less than 10 feet but may be as much as 50 feet in the highest dunes.

?? The upper unit of well-sorted deltaic sand and the overlying deposits of wind-blown sand form the main part of the Sheyenne Delta aquifer—the lower silt unit is generally too fine grained to yield water to wells.

?? Water table fluctuates considerably but most of the time and in most places it is less than 10 feet below the surface.

?? The water table usually is lowest in late winter, just before the spring thaw. During spring thaw there usually is a sharp rise in the water table and the yearly high often occurs within a month or two after the yearly low, changing from 5—10 feet below ground surface to 1 -5 feet below ground surface during April.

?? Following the high in spring or early summer, the water levels generally decline through the summer, fall, and winter. However, unusually large amounts of precipitation in the summer or fall will cause a lessening in the rate of decline or may even produce slight rises in water levels.

?? Winter precipitation has little or no immediate effect because the frost in the ground impedes the infiltration of water. Also, there is little precipitation and that mainly is in the form of snow.

?? The Sheyenne River is eroded as much as 120 feet below the surface of deposition of the deltaic sediments. Accordingly, the water table slopes toward the Sheyenne valley and toward the delta edges.

?? To 1966, no large capacity wells had been drilled in the delta deposits in Richland County—consequently no aquifer tests have been performed as of 1966. Lake Agassiz beach deposits northwest of Hankinson are noted to be similar in character to the deposits of the Sheyenne delta. An aquifer test near Hankinson yield: T = 18,000 gpd/ft, Sy = 0.17 (Powell, 1956, p. 20). 52 hours of pumping.

?? Estimates of T from grain size using method of Keech (1964) (5 locations) resulted in 30,000 gpd/ft near the Richland-Ransom County boundary where the upper sand unit is more than 100 feet thick to less than 500 gpd foot in the southeastern part of the delta where the upper unit is absent.

?? Porosity of cores of deltaic sand deposits ranged from 40 to 48 percent and averaged 43 percent.

?? Specific yield of four cores ranged from 25 to 40 percent (noted to seem "rather high" for deltaic sand deposits as a whole but may be representative for the coarser facies).

?? Estimate of specific yield for the upper part of the deposits made by comparing the rise in water levels in observation wells with precipitation. An average rise of 3.4 feet in 22 wells was attributed to April rains and to a lesser extent by snow melt. The average storage for the upper deposits was estimated to be no greater than 10 percent.

?? In summary, the specific yield for the more permeable (and deeper) delta deposits is likely higher than the average for the delta deposits as a whole.

?? In spring of 1964, an estimated 50,000 acre-feet was recharged over 192,000 acres (3.12 inches). This was considered to be representative of normal spring conditions (based on the changes in water levels in a well that is measured weekly since 1937.

?? The amount of water discharged from the Sheyenne delta through wells is very small compared to natural discharge—the largest yield of any well in Richland County is the municipal well at Wyndmere, which yields about 50,000 gpd.

?? Discharge through springs is large but difficult to make an accurate estimate of.

?? For the 5-year period 1957-1962, the average increase in the Sheyenne River flow for the reach Lisbon to Kindred for October through February was 0.16 cfs per mile of river. Groundwater is attributed to the increase because of low runoff conditions during this period.

?? In spring and summer months the difference in discharge between Lisbon and Kindred is often as great as 100 cfs. Precipitation, runoff, and evapotranspiration are important considerations during this period.

?? Discharge of groundwater through springs (numerous) along the eastern edge of the delta may be 5 to 10 times as great as the fall and winter discharge to the Sheyenne River. Even so, annual discharge through springs is probably less than half of the estimated annual recharge.

?? Hankinson aquifer consists of higher beaches of Lake Agassiz that form a broad belt of sand and gravel extending from the Wild Rice River (north of Hankinson) southeastward to the South Dakota border. The deposits are separated from the Sheyenne delta by an area of till and lake clay.

?? Coarser deposits of Hankinson aquifer are near the south end of Richland County and the material becomes finer grained toward the north. Aquifer test at Sec. 2 T. 130 N, R. 50 W had reported transmissivity of 18,000 gpd/ft, Sy of 0.17 and hydraulic conductivity of 24.4 ft/day (thickness @ 100 feet). Recharge is by direct precipitation and discharge (natural) is mostly by evapotranspiration with some springs at the foot of the higher slopes.

?? City of Hankinson has two municipal wells that tap Hankinson aquifer. Capacities of 500 to 550 gpm.

?? Several small beach aquifers lie outside the Hankinson aquifer. These isolated aquifers are only a few feet thick and a few tens of feet wide but they are highly permeable and will yield small quantities of water to shallow, large-diameter wells. They are recharged by precipitation.

?? About 450 square miles in northeastern Richland County is covered by lake-floor deposits, mostly of clay but in some places the upper part is composed of silt. Silt facies are generally less than 10 feet thick—will yield small quantities of water to large-diameter wells. Unconfined. Generally, water cannot be obtained from the clayey facies of the lake-floor deposits.

?? Four major till aquifers in Richland County:

(1) Milnor channel (shallow valley that extends from Sheyenne valley in Ransom County to the vicinity of Lake Traverse in South Dakota—represents an ice-marginal Pleistocene stream. Sand, sandy gravel, and sandy silt 8 to 66 feet thick and average 40 feet thick. Under unconfined conditions and water levels are generally within 10 feet of surface. Recharge is from precipitation and interaquifer movement form Brightwood aquifer)

(2) Brightwood aquifer: thick body of glacial outwash enclosed by stagnation moraine. About 13 square miles, crops out in high steep face near Elsie on west side of Milnor channel in Brightwood Township. Most outwash is above level of Milnor channel. Thickness ranges from 70 to 130 feet and averages 100 feet. Coarse sand to medium gravel, well sorted. Deposits are only partly covered by till and water is under unconfined conditions. Water discharges into adjacent lakes with elevations below the top of the deposit. Water level is 50 to 65 feet below ground surface. Four feet annual water level fluctuation in 1965. Laboratory hydraulic conductivities are 86 to 160 ft/day. Recharge is from local precipitation. Estimated Sy is 30 percent.

(3) Fairmount aquifer: Buried outwash near Fairmount. Depth of 80 to 110 feet, thickness of 9 to 18 feet, fine to medium gravel overlain by fine clayey sand, under artesian conditions with water level near ground surface. 24 hour pumping test in Fairmount village wells in 1956 at 145 gpm—T=2,500 gpd/ft and storage coefficient = 0.00035. Recharged by overlying till and underlying Dakota Sandstone.

(4) Colfax aquifer: Near Colfax. Sand 100 to 150 feet below surface. @ 50 feet thick, probably buried outwash.

Citations used in this Summary

Baker, C.H., Jr., 1966b. Geology and ground-water resources of Richland County, North Dakota, Part II, Basic data: North Dakota Geol. Survey Bull. 46 and North Dakota State Water Comm. County Ground Water Studies 7, 170 p.

Keech, C.F., 1964. Ground-water conditions in the proposed waterfowl refuge area near Chapman, Nebraska: USGS Water-Supply Paper 1779-E, 55 p.

Baker, C.H., Jr., 1966. Geology and ground-water resources of Richland County, North Dakota, Part II, Basic data: North Dakota Geol. Survey Bull. 46 and North Dakota State Water Comm. County Ground Water Studies 7, 170 p.

Summary

This is a compendium of water-quality data, well construction information, and well logs for Richland County. Includes map of well locations. Cited in other reports.

Baker, C.H., Jr., 1967. Geology and ground water resources of Richland County, Part 1, Geology: North Dakota Geological Survey Bulletin 46 and North Dakota State Water Commission County Ground Water Studies 7, 45 p.

Abstract

Richland County comprises an area of approximately 1,450 square miles in the southeastern corner of North Dakota. About one-fifth of the county is in the Drift Prairie physiographic division; the remainder is in the Red River Valley (basin of glacial Lake Agassiz) physiographic division.

The stratigraphy of the sedimentary rocks underlying the Pleistocene deposits is relatively uncomplicated. Cretaceous Dakota Sandstone lies unconformably on the Precambrian crystalline basement. The Graneros Shale and the Greenhorn Formation, both of Late Cretaceous age, overlie the Dakota in most of the county, and no indurated rocks younger than the Greenhorn are present.

Pleistocene glacial drift mantles the entire county; the known thickness of the drift, including the deposits of glacial Lake Agassiz, range from 154 to 490 feet. Drift representing several ice sheets may be present but cannot be differentiated except in a few places. All of the surficial features of the county can be attributed to the last ice sheet (Mankota advance); local zones of oxidized till, extensive bodies of buried outwash, and buried lake silts are the only indications of the presence of older drift in the subsurface.

The major surficial features of the Drift Prairie in the county are stagnation moraine, a large body of overridden pitted outwash, and an ice-marginal drainage channel. Minor features include end moraine, ground moraine, and kames.

The flat expanse of the Red River Valley is interrupted by the Sheyenne delta and by the major shorelines of glacial Lake Agassiz. The Sheyenne delta is an extensive deposit in Richland County and an important aquifer. It covers 550 square miles and consists of sand and silt as much as 200 feet thick. The lake-floor deposits, where present, may include two distinct lithologies, but the upper unit is thin and irregularly distributed.

Few Pleistocene fossils have been found in Richland County, and most of the available material is of little value for age determinations.

Summary

?? Richland County is in the Central Lowland province of the Interior Plains. The eastern part of the county is in the Red River Valley physiographic division and 300 square miles in the southwestern part of the county is in the Drift Prairie physiographic division. The Red River

Valley can be divided into the Sheyenne delta, which occupies approximately 550 square miles in the northwestern corner of the county and the Lake Agassiz plain.

?? The north end of the Sheyenne delta stands about 100 feet above the lake plain; the delta grades outward into the plain. The delta surface includes many areas of dunes where the local relief is as much as 50 feet within a square mile. Outside of the dune areas, the ground is gently rolling to nearly flat. The Sheyenne River crosses the delta in a steep-sided valley that is as much as 120 feet deep.

?? Much of the Drift Prairie is an area of high relief (50 to 75 feet in a square mile) and nowhere does it approach the levelness of the lake plain.

?? drainage pattern on the Sheyenne delta is poorly developed. Antelope Creek, Elk Creek, and several smaller unnamed streams drain into the Wild Rice River. A number of unnamed streams enter the Sheyenne River from the delta—most of these minor streams are only a few miles long and although spring fed, some are dry during a part of every year. Good subsurface drainage precludes the existence of permanent ponds on the delta but marshy areas are numerous in wet seasons.

?? Most of the soil is of the chernozem type, characterized by black topsoil and limey subsoil. The soils of the Sheyenne delta and the higher beaches are sandy loams, much lighter than the clayey loams. These light soils are subject to wind erosion when plowed and the dune topography makes cultivation difficult. Accordingly, much of this area is used for grazing. A portion of the Sheyenne delta is in the Sheyenne National grassland, administered by the United States Forest Service and is restricted to grazing.

?? Climate is continental in type, characterized by short summers and long cold winters. Summer temperatures above 90-degrees are common and winter temperatures are often as low as 20-below. The average annual precipitation is about 20 inches, most of which falls as rain in the spring and summer.

?? Stratigraphic sequence (USGS Nomenclature):

Age	Unit	Description	Thickness (feet)
Quat (recent)	Alluvium	Silt and clay on flood plains of modern streams	0-40
Quat (Pleist)	Glacial Drift	Glacial till, glaciofluvial deposits, and glacial lake sediments	154-490
Cretaceous	Greenhorn Fm.	Black limey shale, generally contains minute white “specks” of calcium carbonate; interbedded with white to buff limestone	0-212
Cretaceous	Graneros Shale	Black shale, locally with streaks and lenses of white sand; often marine fossils	0-160
Cretaceous	Dakota Sandstone	White quartz sand with interbedded variocolored sandy shale, siltstone, and clayey sandstone	0-238+
Cretaceous (?)	Undifferentiated rocks	Light gray to moderate yellowish-green “nodular” sand, interbedded with varicolored clay	0-61
Precambrian	Undifferentiated crystalline rocks	“Granite.” Generally deeply weathered in upper part	?

?? Geologic History (Pre-Pleistocene):

(1) Much erosion of Precambrian crystalline rocks exposed at the beginning of Cretaceous. Williston Basin was slowly sinking and filling with sediments (Richland County is on the edge of the basin and was probably a source area for the basin sediments.

(2) Cretaceous seas invaded area, covering an irregular and deeply weathered surface. Advance of sea was slow and very shallow water covered the area. Oldest sedimentary rocks in the area are littoral deposits of the Dakota Sandstone and their irregular distribution and varying thickness suggest that many knobs and hills of the granite protrude as islands in the shallow sea. The sea probably retreated briefly after deposition of the Dakota sand and erosion probably removed much of the deposit from the eastern part of the county.

(3) Later, water completely covered the area and black mud (Graneros Shale) was deposited in quiet, brackish water. A few thin beds and lenses of fine sand suggest that the shoreline was not far away. Younger deposits (Greenhorn Formation) contain much interbedded limestone and were probably formed in somewhat deeper water with better circulation. Younger Cretaceous rocks that are present further west (Niobrara, Pierre and other formations) are absent under Richland County. Probably at least some of these rocks were deposited in the area but were subsequently eroded.

(4) After the retreat of the Cretaceous seas, the area again was subjected to erosion. Many of the Cretaceous rocks were stripped away and the weathered basement rocks were exposed again in the deepest valleys. This last long period of erosion was terminated with the advance of the Pleistocene glaciers.

?? Geologic History (Pleistocene)

(1) During Pleistocene, Richland County was covered several times by sheets of glacial ice. Each ice sheet probably left deposits of drift and each succeeding ice sheet probably removed and redistributed part of the deposits of its predecessor. The deposits of the various ice sheets are so similar in lithology that there is no ready means of distinguishing between them. Great thicknesses of glacial drift were deposited and by the time of the last glacial retreat the original topography was completely buried. A portion of the last ice sheet broke off and melted in place and the stagnant ice left characteristic topographic features in the southwestern corner of Richland County. The stagnant ice deposits were overridden by a minor readvance of the glacier and then the final withdrawal of the ice began.

(2) The regional slope in eastern North Dakota is to the northeast as the last ice sheet retreated to the north it blocked the drainage. A large proglacial lake (Lake Agassiz) was formed in eastern North Dakota and western Minnesota. Most of Richland County is within the Lake Agassiz basin. At its maximum, Lake Agassiz extended from northeastern South Dakota to northern Manitoba (more than 550 miles) and had an average width of 150 miles. The greatest depth of Lake Agassiz in Richland County (difference between lowest point on the lake plain and the highest beach) was about 150 feet. The lake had an outlet to the south through a channel now occupied by the Bois de Sioux River and a chain of lakes and marshes. Water flowing out of the lake eroded the bottom of the channel and this deepening of the outlet caused a general lowering of the water level in the lake. The materials in the floor of the channel were not homogeneous; consequently the rate of erosion was not

uniform. During periods of rapid erosion, the lake level fell rapidly; during periods of slow erosion, the lake level changed slowly and well-defined shorelines were formed. As the ice continued to retreat, lower outlets were uncovered to the northeast and Lake Agassiz gradually receded from Richland County. Possibly a readvance of the glacial ice blocked the northern outlets and caused the lake to be refilled to the level of the southern outlet. The effect of the draining and refilling was slight in Richland County; a few scattered deposits of silt on the lake plain may have been deposited during the second stage of the lake.

(3) Many of the surficial features of Richland County were formed in Lake Agassiz. During the highest stage of the lake, a well-defined shoreline (Herman shoreline) was formed and an extensive delta was formed at the mouth of the Sheyenne River. As the ice sheet dwindled and the lake was drained, other beaches were formed at lower levels and parts of the courses of four of these lower beaches can be traced through Richland County. During the life of Lake Agassiz, wave action smoothed the lake floor and a blanket of clay and silt was deposited in the deeper parts of the basin.

(4) When the glacial ice far to the north finally melted and Lake Agassiz was drained, the lake plain had essentially the form that is seen today. Recent erosion has been very slight and the only conspicuous topographic change in Richland County since the drainage of the lake has been the formation of sand dunes on the Sheyenne delta and in the vicinity of Hankinson. These dunes probably were formed very soon after the drainage of the lake and have changed little in recent times.

?? Sheyenne Delta: covers about 750 square miles, of which 550 is in Richland County. It is crossed by the Sheyenne River, which is deeply entrenched into the delta. The northeastern edge of the delta is marked by a conspicuous steep slope, prominent at the Cass-Richland County boundary but it becomes less prominent southward and is barely visible south of Colfax. Near Wyndmere, there is no surface expression of the delta edge and the limits of the delta must be mapped on the basis of the changes in lithology.

?? Sheyenne Delta surface is covered with sand dunes over much of its extent and the topography is strongly rolling. The highest dunes border the Sheyenne valley, were the local relief may exceed 50 feet. Most of the dunes are stabilized by vegetation but there is considerable movement of sand wherever the vegetal cover is broken.

?? Near the Richland-Ransom County boundary, the delta sediments are primarily fine to medium sand but the average grain size decreases eastward. Near the eastern edge, the predominant lithology is very fine sand and silt with some interbedded clay.

?? Stratification is well exposed in only one known locality, near the eastern edge of the delta (west edge of sec. 14, T. 136 N, R. 51 W). Here fine sand, silt, and clay are interbedded and the sand and silt are cross stratified. The most common type of stratification is ripple lamination. Some silt and very fine sand beds are strongly contorted on a small scale. The mode of formation of these contortions is not known but such contortions as well as the ripple laminations are common features of deltaic and flood-plain deposits.

?? An advancing delta is built out over its own bottomset beds as well as over existing lake-floor deposits and it is impossible to distinguish in test holes between delta bottomsets and lake-floor deposits of essentially the same composition; therefore a boundary cannot be established between delta and lake-floor deposits.

?? The greatest thickness of sand penetrated during test drilling on the Sheyenne delta was 107 feet in test hole 2185 (135052-21ccc) but it is questionable whether this figure should be taken as the thickness of the delta deposits at this point—the drill passed from sand into silty clay and the hole was stopped after drilling only a few feet into the clay before reaching the underlying till. The greatest known thickness of sand, silt, and clay; that is, the greatest known depth to glacial till is 198 feet penetrated in test hole K-2R (136-51-7ddd). The average depth to till is 150 feet. The delta sand is only 45 feet thick near the southern edge of the delta and has no clay or silt under it.

?? the steep northeastern slope of the delta is probably a wave-cut slope representing the Campbell shoreline. The entire delta must have been formed before the lake declined to the Campbell level.

Armstrong, C.A., 1982. Ground-water resources of Ransom and Sargent Counties, North Dakota: North Dakota Geological Survey Bulletin 69—Part III and North Dakota State Water Commission County Ground-Water Studies 31—Part III, 51 p.

Abstract

Groundwater in Ransom and Sargent Counties is available from glacial-drift aquifers of Quaternary age and from the Dakota aquifer system of Cretaceous age. Glacial-drift aquifers with the greatest potential for development are the Spiritwood aquifer system and the Bramptom, Elliott, Gwinner, Elglevale, Milnor Channel, Oakes, Sheyenne Delta, and Sand Prairie aquifers. Properly constructed wells in the more permeable parts of these aquifers will yield from 500 to 1,5000 gallons per minute. A total of about 3,000,000 acre-feet of water is available from storage in the glacial-drift aquifers.

Water from the glacial-drift aquifers varies in chemical quality. Dissolved solids concentrations in samples from these aquifers range from 203 to 4,670 milligrams per liter.

The top of the Dakota aquifer system underlies Ransom and Sargent counties at depths that range from 500 to 1,000 feet below land surface. Water in the Dakota is under sufficient head to flow at land surface in most parts of the two-county area. Unrestricted flows from wells tapping the aquifer system generally are less than 10 gallons per minute but may be as much as 50 gallons per minute. Water in the Dakota aquifer system generally is a sodium sulfate type and has dissolved-solids concentrations ranging from 2,170 to 3,340 milligrams per liter.

Summary

?? Climate: subhumid. The mean annual precipitation at Lisbon is 20.19 inches. About 70 percent of the precipitation occurs from April through August. Most of the summer precipitation is from thunderstorms and is extremely variable both in area and in magnitude. The mean annual temperature is 41.8 F. Summer daytime temperatures usually are warm, ranging from 75 to 85. Temperatures exceeding 90 are common in summer. Daily low temperatures are blow o during winter months, especially in January and February.

?? Natural surface drainage in the Lake Agassiz Plain is nearly nonexistent except near the Sheyenne and Wild Rice Rivers, which flow through the Sheyenne Delta. Short tributaries to these rivers have formed, but they only carry runoff for short periods following large storms.

?? Sheyenne delta occupies about 750 square miles in Richland, Cass, Ransom, and Sargent Counties in eastern North Dakota. Approximately 230 square miles of delta is in Ransom and Sargent Counties.

?? Surface area of the delta is generally composed of deltaic materials with thin soils. Shallow depressions of 1 to 10 feet deep and sand dunes as much as 85 feet high have been formed by wind action.

?? The delta deposits in Ransom and Sargent Counties grade from predominantly medium to coarse sand with some lenses of gravelly sand and finer sand and silt in the southwest to predominantly fine to medium sand with a larger proportion of fine sand and silt lenses in the north and east. In the Sheyenne River valley the delta deposits have been removed by erosion and have been replaced by fine-grained alluvial deposits consisting of fine sand, silt, and clay beds. The thickness of the delta deposits ranges from 0 at the edges to as much as 95 feet at test hole 136-053-25aaa. The saturated part of the aquifer ranges in thickness from 6 to 87 feet and has a mean saturated thickness of 41 feet. Downey and Paulson (1974) reported thicknesses as great as 140 feet and a mean thickness of 97 feet; most of their data were from Richland County so apparently the deposits not only are finer grained in an eastern direction, but also are thicker.

?? Yields form individual wells should range from a few gpm near the western edge and the alluvial areas to about 1,000 gpm in areas were more than 35 feet of gravelly sand exists. Variations in yield within short distances may be large, as discovered by a few prospective irrigators who have drilled two to five test holes in the same quarter section before fining a sufficient thickness to yield enough water to supply a pivot system. However, most of the area will yield more than 250 gpm. The yield range for most of the Sheyenne Delta aquifer is 250 to 1,000 gpm because variations in thickness and transmissivity make closer estimates impractical.

?? Recharge to the aquifer generally is from precipitation and snowmelt that infiltrates directly through the sandy soil to the aquifer and from flowing wells in the Dakota. Most of the recharge from precipitation occurs in the spring during the time the frost leaves the ground and before the evapotranspiration loss to maturing crops and high temperatures become significant. Significant recharge also occurs at other times, such as during two storm periods (June 19 and 20, 1975 and June 29 and 30 1975) when more than 5 inches of rain fell during each storm. A digital model of part of the delta area indicates that from 6 to 8 inches of precipitation recharges the aquifers.

?? Water levels rise in the spring due to snowmelt, precipitation, and the release of water from the frost zone. The rise is followed by a sharp decline during the summer months due to evapotranspiration (this sharp decline may be interrupted by large storms). The sharp decline is followed by a more gradual decline that occurs during the autumn season when evapotranspiration is lower and during the winter when capillary water or vapor above the water table is frozen in the soil. Unusual quantities of late fall precipitation can cause water-level rises during the early part of the winter.

?? The gradient of the potentiometric surface in the Sheyenne Delta aquifer is toward the Sheyenne River in areas within a few miles of the river. The steepest gradients are beneath the bluffs on each side of the river valley. Two to 5 miles beyond the river valley, regional gradients become low and local gradients, which are toward individual low areas where evapotranspiration is greatest, mask regional trends.

?? Discharge is by evapotranspiration, pumpage, and underflow into the Sheyenne River and its tributaries in the delta. In 1977, about 830 acre-ft of water was pumped from the Sheyenne Delta aquifer in Ransom and Sargent Counties.

?? The Sheyenne River is a gaining stream throughout the delta area of Ransom and Richland Counties. The gain in Ransom county was about 14 cfs in the fall of 1963. Precipitation in 1963 was about 90 percent of normal so the measured gain probably was lower than would be expected during a year of normal precipitation.

?? In a normal precipitation year, between 1 and 3 inches of the 6 to 8 inches of precipitation that infiltrates to the aquifer as recharge eventually becomes streamflow. The remainder is lost to evapotranspiration.

?? Water from the Sheyenne Delta aquifer is a calcium bicarbonate type. TDS from 28 wells ranged from 203 to 1,150 mg/l with a mean of 386 mg/L. Specific conductances ranged from 400 to 1,700 umho/cm.

?? Sheyenne Delta aquifer has a mean saturated thickness of 41 feet in Ransom/Sargent Counties and an estimated specific yield of 0.15.

?? The city of Lisbon obtains its water from two wells completed in Sheyenne River alluvium or undifferentiated glacial outwash. The maximum possible well yield was not reported but one well was tested at 550 gpm for 20 hours. Reported daily use in 1976 was about 184,000 gallons. A water sample was collected from each well and analyzed—TDS of 773 and 1,060 mg/L; sulfate of 240 and 330 mg/L.

Armstrong, C.A., 1979. Ground-water basic data for Ransom and Sargent Counties, North Dakota: North Dakota Geological Survey Bulletin 69—Part II and North Dakota State Water Commission County Ground-Water Studies 31—Part II, 637 p.

Summary

This is a compendium of water-quality data, well construction information, and well logs for Ransom and Sargent Counties. Includes map of well locations. Cited in other reports.

Bluemle, J.P., 1979. Geology of Ransom and Sargent Counties, North Dakota: North Dakota Geological Survey Bulletin 69—Part I and North Dakota State Water Commission County Ground-Water Studies 31—Part I, 84 p.

Abstract

Ransom and Sargent Counties, located at the eastern edge of the Williston Basin are underlain by 500 to 1,800 feet of Paleozoic and Mesozoic rocks that dip gently to the northwest. The Cretaceous Belle Fourche, Greenhorn, Carlile, Niobrara, and Pierre Formations lie directly beneath the glacial drift, and the Sheyenne River, especially in northwestern Ransom County. The Pleistocene Coleharbor Group, which covers most of the area, consists mainly of glacial, fluvial and lake sediment. The Coleharbor Group averages about 200 feet thick but it is as much as 400 feet thick near Gwinner. The Holocene Oahe Formation occurs in parts of the area, chiefly sloughs, river bottomland, and dune fields. It consists mainly of alluvial and eolian sediment.

Most of the two-county area is part of the Glaciated Plains, an area characterized by nearly level to undulating topography. Rolling to steep land is found along the Sheyenne River valley, on the Prairie Coteau in southeastern Sargent County, in areas of sand dunes in the eastern part of Ransom County, and western Sargent County, and in areas of intense ice thrusting, which are prominent in western Sargent County.

Several distinct till layers that have been identified in Ransom and Sargent Counties attest to repeated glacial advances, both prior to and during Wisconsinan time. Following the earliest flooding of western Sargent County by glacial Lake Dakota, a readvance of the glacier resulted in large-scale thrusting. The early glacial Lake Agassiz flooded eastern parts of the two counties, resulting in discontinuous lake and shore sediments above the Herman level. Later, the Sheyenne Rive built a large delta into the lake while it stood at the Herman level. After r Lake Agassiz drained, wind erosion built large dunes on the Sheyenne Delta.

Summary

?? Beneath the youngest sediments (alluvium and windblown silt) are glacial deposits belonging to the Coleharbor Group, which overlie the Cretaceous Greenhorn, Carlile, Niobrara, and Pierre Formations.

?? Sediment of the Coleharbor Group is exposed throughout Ransom and Sargent Counties. The Colharbor Group in the two counties apparently ranges up to more than 400 feet thick beneath the Whitestone Hills.

?? Holocene sand and silt facies of the Oahe Formation in Ransom and Sargent Counties consists of river and windblown sediment. The river sediment is found beneath flood plains along the Sheyenne, Maple, and Wild Rice Rivers and along some of the smaller streams as well. It is generally light to dark gray sand and silt that has indistinct horizontal bedding. Terrestrial and aquatic fossils such as shells, wood fragments, and bones are common.

?? Windblown sediment is extensive in eastern Ransom County and in parts of western Sargent County. It is typically well-sorted, fine sand with some black, sandy silt that was derived from windblown topsoil. Obscure bedding, indistinct cross-stratification, and weak paleosols can be seen in some exposures. Fossils are uncommon. The windblown sediment, which occurs as dunes or as a nearly flat sheet of sand, generally overlies fluvial sediment of the Colharbor Group (sand and gravel facies), but in some places dunes have blown over areas of till.

?? The Sheyenne River valley crosses Ransom County and includes about two percent of the two-county area. It is about 200 feet deep near Fort Ransom and in that area it has steep, bouldery walls cut mainly in till and in the Cretaceous Niobrara and Pierre Formations. The valley is only about 50 feet deep in eastern Ransom County were it is cut into fine sand and silt of the Sheyenne Delta but over a mile wide in places.

?? It is sometimes difficult to differentiate the sheets of shoreline sand from fluvial deposits. Both types of sediment are closely associated in many places. In the westernmost portions of the Sheyenne Delta, interbedded lake and stream sediments are commonly seen in close association; farther east in Ransom County most of the surface cuts expose stream sediment and the interbedded lake and stream sediment occurs at slightly greater depths.

?? The Sheyenne Delta deposits consist of interbedded lake sediments and river sediments in places and they are covered by a sheet of windblown sand and dunes in places, but river sediment constitutes the largest proportion of the surface materials in the delta.

?? The meltwater trench of the Sheyenne River was mainly carved by water draining from glacial Lake Souris in north-central North Dakota into glacial Lake Agassiz. At the point were this large river of meltwater flowed into Lake Agassiz, it built a delta. It is not known for certain whether the flow was relatively continuous or whether it was a series of periodic, "catastrophic" events. The water flowing out of glacial Lake Souris was probably relatively free of sediment (the sediment having settled out in the lake) and cold and therefore capable of intense erosion; it probably carved the Sheyenne River trench quite rapidly. Evidence of repeated flooding is found in the form of patches of bedded silt in several places on the rim of the Sheyenne trench.

?? Gravel terraces occur within the Sheyenne meltwater trench in several places along its route.

?? Most of the gravel and sand of the river flood plains and terraces is poor in quality, tending to be silty and shaly. The best quality gravel and sand is found on some of the terraces of the Sheyenne River. River terrace gravel contains somewhat less shale and is better sorted than is the river sediment found in meltwater trenches and broad glacial outwash plains.

?? Much of the information on the Sheyenne Delta is the result of research by Dr. John Brophy of the Geology Department at North Dakota State University in Fargo. Dr. Brophy has done much more work on the delta than has anyone else.

?? The delta is characterized by a generally low-relief, east- to northeast-sloping surface that is covered by irregular, partly stabilized hills of windblown sand. Local relief on some of the dunes exceeds 75 feet. The Sheyenne River valley is entrenched as much as 100 feet below the delta surface and exposes an incomplete cross section of the deltaic stratigraphy. The northeast edge of the delta is marked by a 75-foot high, wave-curt scarp that becomes less pronounced southward.

- Generally the lowermost sediments lying on the pre-delta till surface in Ransom and Sargent Counties are gravel and sand deposits that occur in T 132-133N, R 53-54W. These fluvial sediments apparently were deposited by the early Sheyenne River as soon as it abandoned its ice-marginal Milnor Channel position when the glacier margin receded from this four-township area. The gravel and sand is the deepest fluvial sediment in the area, with between 5 and 15 feet of it lying on till at elevations between 950 and 975 feet; these buried fluvial sediments apparently have no lateral equivalent in the two-county area.

- Along the western margin of the delta, in T 133-136 N, R 54W, in Ransom County, sand overlies the till in most places at elevations ranging from about 1,025 to 1,050 feet. These sand deposits are restricted to the location where the river entered the rapidly flooding lake. They become much finer just a short distance eastward, grading into silt and clay, which generally overlies till, but is itself buried in most places beneath windblown materials. The silt-clay unit is largely turbidity-current sediment, which ranges up to over 70 feet thick in parts of eastern Ransom County and is exposed in several places along the Sheyenne River trench.

- Broad areas of the Sheyenne Delta in eastern Ransom County and parts of the glacial Lake Dakota plain in western Sargent County have been subject to intense erosion and deposition by the wind since deglaciation. Wind-blown sediment consists of well-sorted, fine sand with no gravel. Indistinct cross-bedding is found in some dunes. The many dunes and shallow blowouts on the Sheyenne Delta impart a hummocky appearance to the landscape. Dunes about 25 feet high are common with some over 75 feet high near the Sheyenne River in eastern Ransom County.

- The dunes on the Sheyenne Delta lie mainly in the area opposite the old mouth of the Sheyenne River and along both sides of the east-west stretch of the Sheyenne trench. The dunes of the wedge-shaped area spreading from the old mouth of the Sheyenne River represent wind reworking of sandy delta beds but at least some of the dunes along the trench may have originated from river sand laid down during the cutting of the trench. Prevailing wind direction during dune formation appears to have been from the south, although recent blowouts in the area indicate northwesterly winds.

- With the development of vegetation cover, the dunes became more stable, but they are still subject to wind erosion and redeposition wherever the cover is broken. The pattern of eolian activity and resultant distribution of dunes on the Sheyenne Delta seems to be controlled by the presence or absence of a layer of clay that is less than a foot thick in most places where it occurs on top of the ground. Wherever the clay is present, it forms a protective seal, effectively preventing wind erosion; where it is lacking, the sand is free to blow. Groundwater discharge has carried the clay upward, apparently from buried layers of turbidity-current sediment, and deposited it on the surface. In some places, the wind has scoured to the water table, which also acts as a barrier to further downward erosion by the wind.

Sieg, C.H. and P.M. Wolken, 1998. Dynamics of a threatened orchid in flooded wetlands (DRAFT): submitted to 16th North Am. Prairie Conference, July 26-29, 1998, Kearny, NE, 21 p.

Abstract

One of the three largest metapopulations of the western prairie fringed orchid (Platanthera praeclara) occurs on the Sheyenne National Grassland, in southeastern North Dakota. Our study was initiated in 1993 to quantify the effect of flooding on individual orchid plants. A total of 66 plants (33 flowering and 33 vegetative) growing in standing water were permanently marked in 1993; their status was checked at the end of the growing season in 1993 and in subsequent growing seasons (1994-1996). Most (70%) of the flowering plants persisted through the 1993 growing season; those that did not were shorter ($P=0.001$) and had a higher percentage of their stalk submerged through the growing season ($P<0.02$). Only one vegetative plan persisted through the 1993 growing season. The ability of the flowering plants to persist in standing water was attributed to their greater height which allowed some portion of the plant to remain above the water and produce photosynthates needed to produce next season's shoot bud and immature root system. Flowering plants persisted through the first growing season with as much as 75% of their stalk submerged in water. IN 1994, only four plants reappeared; in 1995 only one plant reappeared aboveground. None of the plants that did not persist through 1993 reappeared in 1994 or 1995. By 1996 none of the marked plants were observed aboveground. Although flooding is detrimental to the survival of vegetative plants, its impact must be viewed in a larger context and include data over several years. It is likely that flooding creates suitable moisture conditions on higher landscape positions, provides and important mechanism for see dispersal, and is one of several natural catastrophic events that plays a significant role in perpetuating these wetland systems and associated species.

Summary

?? The western prairie fringed orchid (Platanthera praeclara) is a federally listed threatened plant species found in wetlands of the tallgrass prairie west of the Mississippi River. One of the three largest metapopulations of the orchid occurs on the Sheyenne National Grassland in the southeastern corner of North Dakota.

?? The western prairie fringed orchid is a perennial plant characterized by erratic aboveground growth and flowering. Periods of high orchid numbers, usually linked with above-average precipitation, are followed by years when the orchids have seemingly disappeared.

?? The life history of the western prairie fringed orchid includes two distinct life states: vegetative plants (up to 24 cm tall and having 1 or 2 leaves) that remain vegetative throughout the growing season and flowering plants that develop a hollow flowering stalk early in the growing season and have >10 leaves and average up to 52 cm tall.

?? The orchid regenerates vegetatively during the growing season by forming a new primary tuber and perennating bud which develop into the new root system and shoot for the following growing season. In this manner, populations may persist for some time; however, seed establishment is required for recruitment of new individuals.

?? Densities of flowering orchids on the Sheyenne National Grassland were positively correlated with soil moisture in the current year and total orchid density was correlated with soil moisture in the current and previous year.

?? The Sheyenne National Grassland encompasses 27,244 ha and is managed by the US Forest Service. It is depicted as a tallgrass prairie but a "Sandhill Prairie" is more accurate. Big bluestem (Andropogon gerardii) and little bluestem (Andropogon scoparius) occur through the study area.

?? The western prairie fringed orchid occurs most often in lowland depressions ("swales") associated with the Glacial Sheyenne Delta. A layer of nearly impervious silt interbedded with clay and sand is responsible for the relatively high water table in the swales (attributed to Baker and Paulson, 1967).

?? Woolly sedge (Carex lanuginosa Michx.) And northern reedgrass (Calamagrostis stricta (Timm. Koel.)) and baltic rush (Juncus balticus Willd.) Are common in lowland depressions where the orchid occurs. Blue grama, needle-and-thread, sun sedge, and prairie sandreed grow on uplands.

?? The exposure to environmental stresses such as flooding may have a carry over effect in subsequent growing seasons. Environmental stresses or damage in a previous season during which carbohydrate reserves and perennating tissues were formed, or during the beginning of the current growing season when adequate conditions dictate the growth and survival of a new plant were thought to be cures that influenced the reappearance of plants during a growing season.

?? timing and duration of flooding influences the survival of flooded plants. In 1993 water depth increased in the swales during the growing season. It is likely that plants would be more likely to persist and flowering plants more likely to produce seeds in years when the flooding occurs early in the growing season and then subsides.

?? Few data are available on the long-term impacts of flooding or other stresses on survival of individual plants. Data from this study (i.e. lack of root tissue growth on dormant root systems) indicates that it is unlikely that the plants that did not reappear in 1994 or in subsequent years will ever reappear aboveground in the future.

?? "Although this paper documents that flooding has a detrimental effect on the persistence of some individual orchids occurring in the wettest portions of the landscape, we do not suggest that flooding over the last 4 years has destroyed the metapopulation of the western prairie fringed orchid on the Sheyenne National Grassland. To the contrary, we observed high numbers of orchids on the Grassland in 1993 and in subsequent years. Swales that supported orchids during a drought in the early 1990's have been flooded and devoid of orchids since 1993; yet the presence of orchids on higher landscape positions have resulted in a net increase in orchid numbers on the National grassland beginning in 1993." "...flooding also creates habitats with suitable moisture conditions higher on the landscape and then serves to disperse orchid seeds to these habitats."

Paulson, Q.F., 1964. Geologic factors affecting discharge of the Sheyenne River in southeastern North Dakota: USGS Professional Paper 501-D, p. D177-181.

Abstract

Throughout much of its length the Sheyenne River is fed almost wholly by overland runoff from glacial till. However, in the reach 75 to 145 miles upstream from its junction with the Red River of the north, the Sheyenne drains ground water from sand deposits in the Sheyenne delta, into which its valley is deeply incised. Discharge measurements made in the fall of 1963 indicated an average gain of 28.8 cfs in this reach.

Summary

?? Sheyenne River drains about 9,300 square miles of eastern Northern Dakota; about 4,000 square miles lies in the closed Devils Lake basin.

?? About 10 miles southeast of Lisbon, the Sheyenne enters a broad area of mainly sand deposits that have been described by many workers as deltaic in origin, named the Sheyenne delta (about 800 square miles). The delta is nearly flat in some parts but strongly rolling in others where the sand has been heaped into dunes by wind action. Surface drainage is poorly developed.

?? Thickness commonly exceeds 50 feet and in a few places is known to be greater than 100 feet.

?? On reaching the delta the Sheyenne River turns northward and flows approximately along the contact between the east edge of the drift prairie and the west edge of the delta. Where it leaves the drift prairie, the river swings eastward across the delta. Compared to the channel along the contact with the drift prairie, the channel across the delta is much more sinuous. The distance measured along a straight line between the west edge of the delta and the east edge is about 23 miles but the distance along the river is about 52 miles.

?? The discharge of the Sheyenne River has been measured continuously since March 1938 at Valley City, since September 1956 at Lisbon, since July 1949 near Kindred, and since September 1929 at West Fargo. Since 1949, when Lake Ashtabula was created by completion of Baldhill Dam (13 miles upstream from Valley City), the flow of the river below the dam has been regulated by releases from the lake. Although during extended periods of little or no overland runoff the flow of the river is greater than it was before the dam was built—regulation of the flow does not diminish radically the value of the discharge data for comparative purposes.

?? Because a surface-water divide and a groundwater drainage divide are near the Sheyenne River along the western edge of the delta, only a relatively small amount of groundwater drains westward to the river.

?? A significant part of the increase in the discharge of Sheyenne River along the Delta is due to inflow from short tributaries which head on the Sheyenne Delta and whose base flow consists wholly of groundwater discharge from the deltaic deposits. Several tributaries extend back into the deltaic deposits from both sides of the Sheyenne River valley . The largest of these enters the valley from the south a short distance east of the west boundary of Richland County. Five measurements of the discharge at the mouth of this tributary during the period September 13 to November 20, 1963 averaged 2.2 cfs.

?? The eastern stretch of the Sheyenne River through the Delta is bordered mainly by silt and fine sand that yield only small amounts of groundwater. Also considerable groundwater is diverted eastward or northeastward toward the edges of the scarp rather than into the Sheyenne River valley. The last 5.5 miles before Kindred, the river gains 1.6 cfs. Probably most inflow is derived from sand (at least 12 feet thick in places) along the delta scarp.

?? The Sheyenne River lost 3.4 cfs beyond the Delta.

Shaver, R., June 9, 1998. North Dakota State Water Commission Office Memo to David SprynczNatyk, State Engineer, through Milton O. Lindvig, Director, Water Appropriations Division—Conditional Water Permit Application #5188, 31 p.

Summary

?? On November 24, 1997, Ransom-Sargent Water Users, Inc. (Don Smith) submitted a conditional water permit application to the State Engineer to divert 5550 acre-feet of groundwater annually from points of diversion located in the W1/2 of S. 11, T 134N, R 54W at a maximum pumping rate of 1,300 gpm. The diversion is for municipal-rural-domestic use.

?? At a hearing on February 10, 1998, a letter from Allyn J. Sapa of the US Fish and Wildlife Service was submitted that expressed concern over potential adverse impacts on the western fringed orchid (Platanthera praeclara) as a result of the proposed appropriation. A letter from Steve Williams of the US Forest Service was also submitted that expressed concern over potential impacts on the orchid and plant productivity in the nearby Sheyenne National Grasslands. A letter from Richard D. Nelson of the US Bureau of Reclamation requested that the State Engineer perform an analysis to delineate the maximum area of drawdown influence from the proposed pumping and the effects on groundwater seeps.

?? Conceptual Model of the Sheyenne Delta aquifer

1. Sheyenne Delta occupies about 750 square miles in Richland, Cass, Ransom, and Sargent counties (Armstrong, 1982).

2. Near-surface sediments of the delta grade from very coarse to coarse sands in southeastern Sargent County to very fine silty sands to the north in Cass County and to the east in Richland County (Baker, 1967).

3. Based on 108 test holes, the delta deposits range in thickness from 49 to 140 feet and averaged 97 feet (Downey and Paulson, 1974).

4. In the Sheyenne River valley, the delta deposits have been removed by erosion and replaced by fine-grained alluvial deposits consisting of fine sand, silt, and clay beds (Armstrong, 1982).

5. The base of the Sheyenne Delta is underlain by Lake Agassiz clay deposits and/or till.

6. Base on a textural prerequisite greater than or equal to fine sand, the Sheyenne Delta aquifer occupies an area of about 400 square miles (Baker 1967).

7. The Sheyenne Delta aquifer, for the most part, is unconfined.

8. Recharge to the aquifer is primarily by relatively direct infiltration of precipitation and snowmelt. The land surface over the aquifer area is hummocky because of sand dunes and blowouts. The hummocky topography is an important control on both recharge and discharge processes.

9. To a great extent, the recharge to the Sheyenne Delta aquifer can be characterized as depression focussed (Lissey, 1968). During the winter, a frost zone develops at or near the water table. Snow accumulates in depressions and on adjacent topographic-high areas. In the spring, snow melts before the frost zone dissipates. Snowmelt originating in the upland areas accumulates in depressions from surface runoff because of the inability to infiltrate through the frost zone. Ponded water in depressions infiltrates downward to the saturated zone after the frost zone dissipates.

10. Recharge to the Sheyenne Delta aquifer takes place primarily during the spring. During most summer months, recharge to the aquifer is minor because potential evapotranspiration exceeds precipitation. Summer precipitation events generally are not large enough to overcome soil-moisture deficits and generate recharge. Occasionally, during the fall precipitation exceeds both evapotranspiration and soil-moisture deficits and recharge takes place. Even when recharge does not occur during the fall, soil-moisture deficits generally are reduced, significantly affecting the magnitude of the following spring recharge event.

11. Depth to the water table is generally less than 8 feet. The capillary fringe of water table and root zone are coupled. As a result, natural discharge from the Sheyenne Delta aquifer is due, in large part, to evapotranspiration. Armstrong (1982) suggests in a year with normal precipitation, between 14 and 50 percent of precipitation that infiltrates to the aquifer as recharge eventually discharges to the Sheyenne River. Thus, about 40 to 86 percent of natural discharge from the Sheyenne Delta aquifer is due to evapotranspiration.

12. Within about 2 to 3 miles of the Sheyenne River in northern Ransom and Richland counties, the hydraulic gradient of the aquifer is about 20 to 60 feet per mile (0.0038 to 0.0114). In these areas, depths to water table commonly are greater than 8 feet and the capillary fringe of the water table and root zone are uncoupled. At distances greater than about 2 to 5 miles from the Sheyenne River, regional gradients become low and local gradients, which are toward individual low areas where evapotranspiration is greatest, mask regional trends.

13. The lake Agassiz clay deposits and till both function as aquitards (Downey and Paulson, 1974).

14. In the central part of the grassland (away from the Sheyenne River) the hydrogeologic setting is conducive to the development of numerous local flow systems (cells) in which underflow may be insignificant. Within each local flow system, recharge is from relatively direct infiltration of precipitation and local runoff (snow melt) that occurs primarily during the spring. The capillary fringe of the water table and root zone are coupled and therefore discharge primarily is from evapotranspiration that takes place during the growing season. "Thus, movement of ground water is largely vertical, and flow paths are relatively short."

    ?? The western part of the Sheyenne Delta aquifer consists of stratified, very fine to very coarse sand and gravel deposits.

    ?? "The observation well network in the application evaluation area is insufficient to characterize the shape and configuration of the water table on a local scale." "In unconfined aquifers, the configuration of the water table is a subdued replica of the land-surface topography."

    ?? Specific capacity tests were conducted by drilling contractors on 23 irrigation wells located in the application evaluation area (test duration ranged from 1 to 100 hours). Transmissivity was estimated using the method of Walton (1970). Estimated transmissivities ranged from 1,700 ft**2/day to about 12,000 ft**2/day, with a mean of 5,400 ft**2/day.

    ?? William M. Schuh, Hydrologist Manger, NDSWC summarized storativity calculations for Hecla, Hamar, and Ulen soils (5 sites) in the Oakes aquifer study area in Dickey-Sargent counties (December 31, 1990 memo). Specific yield was calculated from total porosity, laboratory wetted porosity, and fielded wetted porosity. Results of study indicate little difference in specific yield between the zone of pedogenesis and the underlying coarse parent materials. Mean values of specific yield by layer were close to 0.25. Based on this, specific yield for Sheyenne Delta aquifer is 0.25 in the study area.

    ?? Water levels remain relatively stable during the winter when recharge does not occur and evapotranspiration is greatly reduced.

    ?? Discharge to the Sheyenne River is negligible along the western flank of the aquifer. A "20- to 40-foot difference in water-level elevations between the westernmost irrigation wells and the Sheyenne River" "indicates a poor hydraulic connection between the aquifer and the river in this area." In this area, the Sheyenne River is incised into the glacial till.

    ?? The average annual irrigation application rate from 1977 through 1996 is 9.7 inches per acre in the western portion of the aquifer (permit application area). Compared to the mid to late 1980s, irrigation water use decreased significantly beginning in 1993, due to wetter, cooler growing seasons.

    ?? Water-level fluctuations caused by irrigation withdrawals are masked by water-level fluctuations caused by natural variations in recharge and discharge (primarily evapotranspiration) as dictated by changing patterns of climate.

?? The State Engineer allocated groundwater with a "sustainable yield" management framework for the Sheyenne Delta aquifer because the annual recharge in many years is relatively large in relation to the volume of water in storage (i.e. water is renewable). The sustainable yield in the Sheyenne Delta aquifer is equal to the long-term average volume of groundwater discharged by evapotranspiration and underflow to the Sheyenne River. "Thus, as water is pumped from the aquifer the volume of water discharged by evapotranspiration and to the Sheyenne River will be diminished. Diminishment of groundwater evapotranspiration requires the decoupling of the plant root zone from the capillary fringe of the water table.

?? The Sheyenne Natural Grasslands occupy about 110 square miles in the central part of the Sheyenne Delta aquifer (about 28 percent of the aquifer), from which groundwater withdrawals (pumping) will not likely occur.

?? The State Engineer has approved an annual appropriation of 19,123.9 acre-feet from the Sheyenne Delta aquifer. This appropriated volume is 15 percent of the average annual recharge of groundwater in the practical development area of the delta.

?? Allocations of appropriation are not made using digital groundwater flow models. Instead, an on-going assessment of aquifer response as related to a specific amount of groundwater development is used. Assessment of aquifer response is accomplished by water-level, water-quality, and water-use monitoring, coupled with an evaluation of climate data, aquifer properties and boundary conditions.

?? "Federal agencies must ensure that nay action they authorize, fund, or carry out is not likely to jeopardize the listed (endangered or threatened) species or its critical habitat. If a federal agency determines that any such proposed action may adversely affect the listed species or its critical habitat, the agency must engage in formal consultation with the listing agency (in this case, the FWS)."

?? During dry, warm climate periods the root zone and capillary fringe of the water table can become uncoupled.

?? A conservative "worse-case" are of influence for a pumping well and associated drawdown distribution would result over a seven-year pumping period with no aquifer recharge. ("Note that even during the dry periods of the 1930s and 1950s, annual recharge rates of between 1 and 4 inches occurred).

?? Recommended the appropriation as long as the right of prior appropriators will not be unduly affect; the proposed means of diversion or construction are adequate; the proposed use of water is beneficial; and the proposed appropriation is in the public interest.

Citations in Summary

Armstrong, C.A., 1982. Ground-water resources of Ransom and Sargent Counties, North Dakota: North Dakota Geological Survey Bulletin 69—Part III and North Dakota State Water Commission County Ground-Water Studies 31—Part III, 51 p.

Baker, C.H., Jr., 1967. Geology and ground water resources of Richland County, Part 1, Geology: North Dakota Geological Survey Bulletin 46 and North Dakota State Water Commission County Ground Water Studies 7, 45 p.

Downey, J.S. and Q.F. Paulson, 1974. Predictive modeling of effects of the planned Kindred Lake on ground-water levels and discharge, southeastern North Dakota: USGS Water-Resources Investigations 30-74, 22 p.

Lissey, A., 1968. Surficial mapping of ground-water flow systems with application to the Oak River basin, Manitoba: University of Saskatchewan, Ph.D. Thesis, 105 p.

Walton, W.C., 1970. Groundwater Resource Evaluation: McGraw-Hill Book Co., New York, NY, 664 p.

Cowdery, T.K. and K. Goff, 1994. Nitrogen concentrations near the water table of the Sheyenne Delta aquifer beneath cropland areas, Ransom and Richland Counties, North Dakota: Proceedings of the North Dakota Water Quality Symposium, Fargo, North Dakota, March 30-31, 1994, North Dakota State University Extension Service, p. 89-102.

Summary

?? Purpose: land-use study to examine the human activities and natural factors affecting the quality of shallow (within 3 meters of land surface) groundwater underlying agricultural areas on the glacial, near-shore deltaic-facies deposits of the Sheyenne Delta. The Sheyenne Delta was selected for this study because it is a surficial aquifer and is susceptible to contamination from the land surface.

?? Homogeneous land use patterns and local groundwater discharge to the Sheyenne River simplify groundwater constituent sources and make the Sheyenne Delta an excellent land-use study site. Cattle grazing is the main use of public lands (Sheyenne National Grassland). On private land, land uses are crop production (corn and sunflowers, most of which are irrigated from the surficial aquifer with lesser amounts of soybeans, small grains, cattle forage, and potatoes) and cattle grazing.

?? Paper is a review of both the 1993 nitrate-nitrogen data collected by NAWQA study and historical nitrate-nitrogen data. Purpose of study is to (1) describe nitrate concentrations near the water table beneath cropland areas after the early part of the 1993 growing season (2) relate nitrate concentration to spatial changes in land use and geology; groundwater recharge and depth to water table; and precipitation and (3) to suggest explanations for these relations.

?? Samples were collected from 29 randomly selected wells during July and August 1993. Seven existing and 22 newly constructed wells form the network sampled for this study. The seven existing wells were installed by the NDSWC or the USGS during 1963 or 1972.

?? Rainfall on the Delta during the 1993 growing season was 166 percent of average for last 31 years.

?? Historical nitrate concentrations come from 70 samples by the NDSWC and 3 by USGS. These data were grouped into (1) High Nitrate (> 0.68 mg/L); (2) Medium Nitrate (0.23-0.68 mg/L) and (3) Low Nitrate (<0.23 mg/L)

?? Samples with high to medium concentrations cluster on the west (beach) side of the delta, south and east of the Sheyenne River and west of the Sheyenne National Grassland.

?? Progradation of the delta into a water body resulted in a general trend of increasing grain size in both the upward and beachward directions. Therefore the Delta aquifer should generally be hydraulically less conductive toward the east-northeast—this trend is documented by Downey and Paulson (1974) who also noted that the entire delta thins to the west as the Lake Agassiz basin approaches the surface.

?? Shallow, high-production irrigation wells and crops such as corn and potatoes (that thrive in coarser-grained irrigated soils) are found most commonly on the western part of the delta. The deltaic deposits are also most homogeneous in this area.

?? Because nitrogen application rates are greatest on potatoes and corn corps, it is reasonable to expect that the shallow ground water in the western part of the delta has the highest concentrations of nitrate in the study area. Nitrates may also be concentrated by pumping high-nitrate groundwater for irrigation.

?? As water table rises, the time required for infiltrating water to reach the water table (lag time) decreases. This lag time increases in December when water table depth increases.

?? Microbial denitrification in groundwater is not a likely mechanism for lower nitrate concentrations in wet years. DOC concentrations are too low.

Downey, J.S. and Q.F. Paulson, 1974. Predictive modeling of effects of the planned Kindred Lake on ground-water levels and discharge, southeastern North Dakota: USGS Water-Resources Investigations 30-74, 22 p.

Abstract

A digital model was used to describe a ground-water system in glacial deltaic deposits near Kindred, North Dakota, and to predict the effects of a planned lake on ground-water levels and ground-water discharge. A digital computer was used to solve the finite-difference equations for ground-water flow.

The model analysis delineated an area of about 140 square miles that would be affected by rising water levels as a result of the lake. The rise of water levels depends on time and hydraulic properties of the aquifer. The maximum projected rise in water levels should occur in about 50 years. Evapotranspiration from the water table is presently near maximum and therefore the projected water-level rise will not be controlled by evapotranspiration. Existing artificial drains will be effective in limiting the extent of water-level rise.

Summary

?? Study evaluates a proposal by the US Army Corps of Engineers to build a damn on the Sheyenne River 5 miles southeast of Kindred, forming a lake in the Sheyenne River valley with normal pool of 984 ft MSL, design pool of 1,017 ft, MSL, and Maximum pool of 1,020 ft, MSL. At normal operating pool the lake would extend westward from the dam a distance of 13 miles and would have a maximum width of about 1 miles. At the Richland-Ransom County line the lake would be confined to the river channel.

?? The study was undertaken to evaluate groundwater effects due to the damn. A digital groundwater model was used to perform the evaluation.

?? The Sheyenne River channel is sinuous and is incised about 15 to 25 feet below the flood plain.

?? East of State Highway 18, several short tributaries, generally less than 2 miles long have been eroded from the Sheyenne River back into the delta deposits. This area is underlain by deposits containing less sand and having less infiltration capacity than areas to the west.

?? Much of the surface, particularly west of State Highway 18, is covered by native grasses and ins included in the Sheyenne National Grasslands administered by the US Forest Service. Extensive growths of native trees (mainly oak and aspen) are interspersed with the grasslands. The flood plain of the Sheyenne River is forested with cottonwood, elm, ash, and basswood.

?? Deposits of till and associated stratified drift underlie the entire area and are exposed in the extreme western part near Sheldon. The till is an unsorted and unstratified mixture of glacially deposited rock debris, primarily clay and silt but containing varying amounts of larger fragments, including boulders. It is rather cohesive, highly calcareous, and in the subsurface, generally olive gray. The stratified drift consists of interspersed layers of sorted and stratified materials ranging from clay to gravel and generally constitutes small percentages of the overall thickness of the deposits. They have low transmissivity and function as lower and lateral (on the west and south) confining beds in the groundwater flow system. The till is underlain by shales of Late Cretaceous age.

?? Highly plastic dense clay of Lake Agassiz deposits are found at depths of about 100 feet except in the Sheyenne River valley. These clay deposits probably represent the lake-floor sediments of glacial Lake Agassiz. The thickness ranged from 6 to 24 feet and averaged 49 feet. They have a very low transmissivity and function as lower confining beds in the groundwater flow system.

?? Sheyenne delta deposits underlie most of the area except in the Sheyenne River valley where they have been removed by fluvial erosion. The deposits generally form the surface materials but in many places have been modified into sand dunes by wind action. They range in thickness from 49 to 140 feet and average 97 feet. The deposits grade from predominantly sand in the southwest to predominantly silt and clay in the northeast, with a corresponding decrease in hydraulic conductivity. The sand is primarily very fine to fine grained and grades northeastward into silt and clay through a transition zone of interbedded sand and silt. The delta deposits and associated sand dunes form an aquifer of considerable extend and importance in southeastern North Dakota and comprise the major aquifer of this study.

?? Deposits of interbedded sand, silt and clay with numerous small mollusk shells underlie the Sheyenne River valley and are well exposed in channel walls. In 16 widely distributed test holes, the thickness of the deposits ranged from 29 to 70 feet and averaged 51 feet. The deposits are believed to be mainly fluvial in origin but may be partly lacustrine. The sand beds seem to be more dominant in the west and the silt and clay beds in the east. The alluvial deposits form an aquifer that probably has hydraulic properties similar to those of the Sheyenne delta aquifer and for the purposes of this study are considered to be an integral part of that aquifer.

?? Transmissivities are largest in the sand facies of the delta deposits (@ 1,400 ft**2/d) and smallest in the silt-clay facies (200 ft**2/day).

?? Only one pumping test produced a specific yield value that was believed to be valid (17%) - the others were much too low because of incomplete drainage.

?? There is very little surface runoff, except in the steep slopes adjacent to either side of the Sheyenne river, its tributaries, and along the delta scarp.

?? Water that infiltrates the soil must first satisfy field moisture requirements. The excess percolates downward to the saturated zone in which the water moves laterally toward areas of discharge long the river and delta front, which are at low elevations. The hydraulic gradients as determined from water levels ranged from 5 ft/mile (0.00094) to 100 feet per mile (0.019). The steeper gradients occur in the bluffs adjacent to the Sheyenne River valley in the northeastern part of the area.

?? The major areas of groundwater discharge are in the Sheyenne River and its tributaries, the Sheyenne delta scarp, several manmade drains on the upland surface of the delta, and where the water table is near land surface, by evapotranspiration.

?? Depth to the water table is greatest in early March, just prior to spring thaw (Baker and Paulson, 1967) and least in early April, just after spring thaw. In most of the area the maximum water-level depths are between 5 and 10 feet below land surface and the minimum depths are 2 to 5 feet.

?? There is evidence of "ridges" of high groundwater levels bordering both sides of the valley. These ridges appear to be related lithologic changes in the aquifer and residuals from previous periods of recharge.

?? The Sheyenne River winds its way eastward through the delta for a distance of about 52 river miles, effectively dividing the aquifer into north and south units. Previous work (Paulson, 1964) had indicated a marked increase in river discharge eastward through most of the aquifer as a result of groundwater inflow. The discharge measurements by Paulson (1964) were limited to the mainstem and did not include tributaries directly.

?? Low-flow stream measurements were made during this investigation - most in tributaries. The measurements were made in May and August 1972. The measurements indicated an increase in river discharge of 109 cfs and 29.4 cfs respectively. The large difference between the two discharge increases is attributed mainly to evaporation, which normally is low in May but near maximum in August. Some of the difference is attributed to steeper hydraulic gradients in May, resulting from recharging spring rains and snowmelt, with consequently higher rates of groundwater movement.

?? Of the 109 cfs increase in discharge measured in May 1972, 17.4 cfs was measured in the tributaries. Of the 29.4 cfs increase in August, 7.6 cfs was in the tributaries. These data indicate that about 84 percent of the discharge measured in May and about 73 percent measured in August was received as seepage inflow through the channel of the Sheyenne River. Furthermore, measurements were made at several points along the lengths of the tributaries and the data showed a fairly uniform increase in discharge, as would be expected in a normal groundwater discharge pattern.

?? Flow model was Pinder and Trescott, slightly modified. Single layer, 33 rows and 50 columns with constant cell dimensions of 2,000 feet.

?? Average K for each cell ranged form 0.1 ft/d to 30 ft/d. Specific yield values were set at 0.2 except when analyzing steady-state conditions.

?? Several natural and manmade streams, including the Sheyenne River and planned lake were modeled as constant head boundaries.

?? A potential evaporation rate of 30 inches per year was used in conjunction with several soil types to calculate evaporation. The evaluation of effects of evaporation from the water table indicates that little change in evaporation will occur with a rising water table because the present water table is so near land surface that evaporation is now occurring at the maximum rate possible fro the existing climatic conditions (note: this assumption was made probably because they did not have the tools to handle variable evapotranspiration terms in the model).

?? The model has the following assumptions:

1. Sheyenne delta aquifer is an extensive groundwater body with boundaries generally beyond the effects of the planned lake.

2. The geologic materials underlying the aquifer form a relatively impervious barrier to the flow of water.

3. The shoreline of the lake will form an aquifer boundary along with the change in head equal to the difference between the present water table and the planned lake surface.

4. Perennial streams, springs, and drains, are in hydraulic connection with the groundwater system.

5. Recharge and discharge from the groundwater system are equal.

6. At any given point within the aquifer the vertical flow component is very small in comparison to the horizontal component.

?? Model calibration was obtained by comparing the output from the various simulation with the mean groundwater level for the period September 1972 through August 1973. Recharge to the model system was adjusted so that the calculated water levels from the simulation were in close agreement with the mean water levels. Calculated discharge from the model to the Sheyenne River corresponded well with the 14-day mean flow for that part of the Sheyenne River including included in the modeled area. Model calibration was directed towards having the model reproduce, as close as possible, the mean water levels.

?? Results of Study:

1. Water level and streamflow data indicate that the Sheyenne River in the reaches of the planned Kindred lake is in hydraulic connection with aquifers in the Sheyenne delta deposits and alluvial deposits in the Sheyenne River valley.

2. The lake will inundate most of the aquifer in the alluvial deposits and will cause groundwater levels to rise 1 foot or more in the Sheyenne delta aquifer for a distance of as much as about 4 miles from the lake shore.

3. Evapotranspiration from the aquifer is presently near the maximum potential evaporation rate for the area and projected rises in water levels probably will not cause an increase in evapotranspiration.

4. Considerable time will be required for the rise in water levels to occur several miles back from the lake. The maximum projected rise in water levels should occur about 50 years after filling of Kindred Lake.

5. The streams and manmade drains will limit the extent of water-level rise

6. The planned lake will cause only slight increases in groundwater discharge from springs and seeps. Most of the increase will be east of the dam and should not exceed 1 cfs.

Armstrong, C.A., 1981. Supplement to: Predictive modeling of effects of the planned Kindred Lake on ground-water levels and discharge, southeastern North Dakota: USGS Open-File Report 81-646, 15 p.

Abstract

A digital model was used to describe a ground-water system in glacial deltaic deposits near Kindred, North Dakota, and to predict the effects on ground-water levels of a planned lake at 950-, 960-, 970-, 984-, and 995-foot stages. This model is a supplement to an earlier model of the ground-water system for a planned lake at the 984-foot level.

The model analysis indicates that only the area within about 2 miles of the present Sheyenne River would be affected by rising water levels as a result of a lake stage at 995 feet. The rise of water levels depends on time and hydraulic properties of the aquifer. The maximum projected rise in water levels is expected to occur in about 50 to 100 years. Evapotranspiration and existing drains will be effective in limiting the extent of water-level rise.

Consequently, the area affected by rising water levels at each lake stage will be much smaller than that shown by the earlier model at the 984-foot stage.

Summary

?? The study was initiated to supplement Downey and Paulson (1974) in response to the Corps of Engineers request for evaluating the effects of the planned Kindred Lake on ground-water levels. The lake levels include elevations above and below the original 984-foot level.

?? The area receives about 20 inches of precipitation annually (1972 through 1977) of which about three fourths occurs during the May through October growing season. Somewhat more than 82 percent of the annual evaporation of about 30 inches also occurs during the same period.

?? Data collected between 1972 and 1977 indicate that water levels throughout the delta rise during cool periods when evapotranspiration rates are small and recharge (from precipitation and snow melt) rates are considerably larger than the yearly average rate. These conditions generally occur every spring and apparently on occasions when the weather is cooler than usual and precipitation is larger than normal, can extend into summer.

?? Modifications to model of Downey and Paulson (1974):

1. Node spacing was changed from 2,000 ft on a side to 500 ft on a side or 500 x 1000 ft. Node spacing in less critical areas was changed to as much as 4,000 ft wide and as much as 7,900 feet long. The change in node size necessitated expanding the size of the model. The lake stages of 950, 960, 970, 984, and 995 ft were simulated by using a 71 by 98 node model.

2. The model was terminated at a groundwater divide north of the Sheyenne River and in an area with an almost flat groundwater gradient south of the river. About one-half of the southern boundary is also along a groundwater divide. These boundaries are nearly the same as those used by Downey and Paulson (1974). The western boundary, however, was shortened to the node that includes the Sheyenne River at an altitude of 995 feet.

3. New land surface elevations at each node were determined using 5-ft contour maps. In some areas, elevation variations of as much as 50 ft existed within a node spacing and an elevation near the mean was used.

4. Changes in node spacing required new hydraulic conductivities at each node but the changes were made with the values shown by Downey and Paulson (1974, pl. 3).

5. Tributary drains to the Sheyenne River were modeled as partially penetrating streams instead of constant-head nodes as in the original model.

?? Soil developed on the aquifer is porous and permeable. Thompson and Sweeney (1971) estimated vertical permeability equivalent to infiltration rates of 2 to 6.3 inches per hour in soils similar to those in the delta. These rates are sufficiently high to preclude most runoff except when the ground is frozen, during extremely intense precipitation periods, or when the water table is very close to the land surface.

?? Through experimentation, combinations of recharge and evapotranspiration rates were found that do not exceed empirical evaluations of the aquifer and soil characteristics. These combinations were used in calibrating the model. The range of values for aerial recharge was between 20 and 40 percent of the total annual precipitation of 20 inches. The use of values of less than 20 percent provided insufficient recharge to compensate for flow to the Sheyenne River. Values in excess of 40 percent produced unrealistic simulated water levels.

?? Downey and Paulson (1974) considered evapotranspiration to be operating at near maximum potential rates in most of the area and therefore, did not include a function of this process in their model. This modeler did not agree with this basic assumption because water levels under much of the area are too deep for maximum potential evapotranspiration to be effective. The two-dimensional model in this study allows input of only a linear evapotranspiration function with a maximum rate at land surface and a zero rate at a fixed depth. The average annual maximum potential evaporation rate in an area including the Sheyenne Delta aquifer is about 30 inches.

?? Ripple, Rubin, and van Hylckama (1972) describe a technique by which homogeneous soil types such as those in the delta may be evaluated for rates of evaporation. Calculations based on this technique show that evaporation can occur at rates close to the potential rate for depths to the water table of as much as 7.2 feet depending on soil permeabilities. The potential rates and depths are in part meteorologically controlled and the maximum potential rates and depths occur only during the hotter summer months. It was necessary to vary rates and depths of effective evapotranspiration using various recharge rates to arrive at a balance between the two rates that simulated steady-state values. A range of values for maximum evapotranspiration from 25 to 35 in per year was found to be in balance with the range of recharge rates described. Maximum depths of 6 to 10 feet for the effective evapotranspiration proved to fit best with observed steady-state conditions. Other modelers, modeling settings similar to the delta in North Dakota, came up with recharge ranges of between 7 and 8.25 inches per year and effective evapotranspiration depth limits of 8 feet.

?? The average depth limit of evapotranspiration in this model was set at 8 feet. Recharge was set at 7.4 inches per year, giving the best fit of simulated to measured water levels during calibration, suing the assumed values of evapotranspiration.

?? Calculated discharge of about 30 cfs from the aquifer to the Sheyenne River corresponded with the low-flow measurements for the Sheyenne River in the delta.

?? Results and Conclusions:

1. Water-level and streamflow data indicate that the Sheyenne River in the reaches of the planned Kindred Lake is in hydraulic connection with aquifers in the Sheyenne delta deposits and alluvial deposits in the Sheyenne River valley.

2. The areas affected by water-level rises of 1 foot or more are larger at each succeeding higher lake stage. However, even at the 995-foot lake stage, the area affected by a rise of 1 foot is smaller than the area shown to be affected by the 984-foot stage by Downey and Paulson (1974) in the earlier model. The difference in the modeled results is due primarily to the effects of evapotranspiration and, to a lesser extent, to the greater control in the model of the natural drains due to smaller node spacing.

3. Where the lake will inundate only the Sheyenne River flood plain, ground-water levels will rise 1 foot or more in the delta aquifer only in those areas near the lake and beneath the steeply sloping valley sides. Where the lake encroaches upon the steeper sides of the valley, water-level rises of more than 1 foot will be restricted to areas where present water levels are more than 5 feet below land surface. By comparing projected water-level

rises at the 995-foot stage with the present depth to water and using an effective evapotranspiration depth of 6 feet, water-level rises of more than 1 foot generally would be restricted to areas where present water levels are more than 100 feet below land surface.

4. If actual effective depth of evapotranspiration is between 6 and 10 feet and recharge is not more than 8.25 inches, water levels will not change appreciably more than 2 miles from the present river at lake stages of 995 feet or lower.

5. The tributaries and manmade drains as well as evapotranspiration will limit the extent of water-level rise.

6. Considerable time will be required for the maximum rise in water levels to occur. Within the area between the lake shore and the 1-foot rise line, the water-level rise will be progressively larger toward the lake. Based on available data, the maximum projected rise in groundwater levels at each lake stage will occur several decades after filling of Kindred Lake. Various computer simulations indicate that the maximum projected rise in groundwater levels should occur in about 50 to 100 years. The model assumes a steady-state condition has been reached when there is less than 0.01 feet rise in 30 years.

Cited References in Summary

Downey, J.S. and Q.F. Paulson, 1974. Predictive modeling of effects of the planned Kindred Lake on ground-water levels and discharge, southeastern North Dakota: USGS Water-Resources Investigations 30-74, 22 p.

Ripple, C.D., J. Rubin, and T.E.A. van Hylckama, 1972. Estimating steady-state evaporation rates from bare soils under conditions of high water table: USGS Water-Supply Paper 2019-A, 39 p.

Thompson, D.G., and M.D. Sweeney, 1971. Soil survey, LaMoure County and parts of James River valley, North Dakota: US Dept. Of Agr., Soil Cons. Serv., 119 p.

Hopkins, D.G., 1996, Hydrologic and abiotic constraints of soil genesis and natural vegetation patterns in the sandhills of North Dakota: Ph.D. thesis, North Dakota State University.

Summary

?? The Sheyenne Delta aquifer is a calcium-bicarbonate type water characterized by low salinity and sodium content.

?? Water from the Dakota aquifer enters the Sheyenne Delta aquifer only as flowing wells. The water is seven times more saline and nearly 40 times higher in sodium than water in the Sheyenne Delta aquifer. The Dakota aquifer is classified as a sodium-sulfate type but chloride is the dominant anion in 10 of 74 wells tested.

?? Two new land use practices are occurring in the sandhills: one is management response to a natural, though undesired, example of plant succession, (leafy spurge has infested approximately 19% of the Sheyenne National Grasslands and significantly reduced rangeland productivity and stocking rates) the other a result of economic opportunities in agriculture.

?? Both the USFS and private landholders in the sandhills are applying 2,4-D and picloram (Tordon) to control leafy spurge. The threat these herbicides pose to groundwater quality has not been assessed in the Sandhills.

?? In the past, local irrigation has been dedicated to corn for grain or silage, but irrigated potato production has increased rapidly in the Sandhills during the last few years. Corn acreage is being converted to potato production and several large storage facilities have been erected. Ransom County acreage planted in irrigated potatoes was virtually nil in the mid-1980s and was about 1134 hectares in 1994. The number of application permits to withdraw water from the Sheyenne delta aquifer for irrigation has increased markedly.

Kelly, T.E., 1966. Geology and ground water resources, Barnes County, North Dakota, Part III-Ground water resources: North Dakota Geological Survey Bulletin 43 and North Dakota State Water Commission County Ground Water Studies 4, 67 p.

Abstract

There are two major types of aquifers in Barnes County, those in consolidated rocks and those in unconsolidated glacial deposits.

The Dakota Sandstone in the principal aquifer in the consolidated rocks. The average artesian flow from the aquifer is less than 10 gpm (gallons per minute), but flows exceeding 700 gpm are reported. The water is highly mineralized. Small yields of water are obtained from the Pierre Shale.

The Spiritwood aquifer is the most productive Barnes County aquifer composed of unconsolidated glacial deposits. Individual well yields of 1,000 gpm are available locally and the water is generally of good quality. There are numerous other glacial aquifers in the county. Only Valley City and Kathryn have adequate supplies of good-quality water. Several other communities have suitable ground-water supplies potentially available to them, but these are not yet developed.

Findings:

- The Sheyenne River has eroded more than 200 feet below the surrounding plain.
- The only area that is not eroded into the bedrock where it follows an exhumed channel, south of Lake Ashtabula.
- Glacial drift is the dominant surface sediment nearly everywhere but in the Sheyenne River valley.
- Two dominant end moraines have been mapped in the county: the Luverne and the Kensal-Oake.
- The Sheyenne River and the Baldhill Creek channels have eroded below the water table.

- Porosity and permeability of the Dakota Sandstone in this area is not well-defined. Thickness is not uniform and there is little data on the physical characteristics.
- For the Pierre Shale, the coefficient of transmissibility range from 490 to 900 gpd per foot. The average value was 710 gpd. The computed values of the coefficient of storage ranged from 2.8 x 10^{-4} to 5.8 x 10^{-4} and had an average value of 4.2 x 10^{-4} (Aronow, Dennis, and Akin, 1953, p. 76).
- Water in the Spiritwood aquifer is confined under artesian pressure. Water levels in the aquifer rise more than 100 feet over the aquifer where possible. Aquifer tests in the aquifer show transmissibility of the aquifer to range between 22,000 and 96,000 gpd per foot and permeability to range from 320 – 4,150 gpd per square foot.
- Other aquifers in this region include: Wimbledon, Bantel, Till, Valley City, Sand Prairie, and Stoney Slough.

Citations used in this Summary

Aronow, Saul, Dennis, P.E., and Akin, P.D., 1953. Geology and ground-water resources of the Michigan Cite area, Nelson County, North Dakota: North Dakota Ground-Water Studies no. 21, 125 p.

Kelly, T.E. and Block, D.A., 1967. Geology and ground water resources, Barnes County, North Dakota, Part I-Geology: North Dakota Geological Survey Bulletin 43 and North Dakota State Water Commission County Ground Water Studies 4, 51 p.

Barnes County, in southeastern North Dakota, has an area of approximately 1,500 square mils. The physiographic features are the result of glaciation. Most of the county is characterized by gently undulating plains of ground moraine separated by relatively narrow, elongate end moraines. Although most of the area lacks an integrated drainage system, the deeply entrenched Sheyenne River traverses the county from north to south. The Continental Divide, which separates the Gulf of Mexico and Hudson Bay drainages, crosses the western part of Barnes County.

Rocks of Cambrian and Ordovician age are separated from Cretaceous strata by an angular unconformity. The Cretaceous rocks are subdivided into the Dakota Group, the Colorado Group, and the lowest formation of the Montana Group. These units dip westward into the Williston Basin. In Barnes County, the total thickness of these consolidated tocks is about 2,400 feet.

The bedrock surface, which was eroded on shales of the Colorado and Montana Groups, generally slopes from west to east at about 15 feet per mile. The Spiritwood channel, a major southward-trending bedrock channel, was eroded more than 250 feet deep prior to glaciation. This channel and its tributaries underlie much of western Barnes County and adjacent Stutsman County.

The landforms and drainage systems of the county were formed during the late part of the Wisconsin glaciation. At least seven distinct drifts are present in Barnes County. These were differentiated mainly on the basis of landform father that lithology. The Millarton, Eldridge, Buchanan, and Cooperstown drift sheets were all formed at the margin of a receding ice mass, whereas the Kensal-Oakes and Luverne drifts are associated with significant readvances of the ice mass. An additional drift unit, the Sheyenne Valley drift, is exposed in the valley of the Sheyenne River, but its relative age and aerial distribution are problematical.

Lake Lanona was ponded when the Luverne ice mass blocked the Sheyenne River. This proglacial lake had an area of about 160 square miles, and inundated most of central Barnes County.

Bald Hill Creek and the ancestral Sheyenne River originated as meltwater channels during the Cooperstown phase of glaciation, but the present headwaters of the Sheyenne were not established until Luverne time. Throughout much of its early history, the Sheyenne River emptied into the James River. Following ice withdrawal from Barnes County, but prior to Lake Agassiz, it drained into the Minnesota River via an ice marginal channel called the Milnor channel. Its present course east of Lisbon was established while Lake Agassiz was in existence and, also, subsequent to drainage of the lake.

Findings:

- ✍ Quaternary deposits include alluvial deposits and glacial drifts which include: Sheyenne Valley Drift, Millarton Drift, Eldridge Drift, Buchanan Drift, Kensal-Oakes Drift, Cooperstown Drift, and the Luverne Drift

Kelly, T.E., 1967. Geology and ground water resources, Barnes County, North Dakota, Part II-Ground-Water Basic Data: North Dakota Geological Survey Bulletin 43 and North Dakota State Water Commission County Ground Water Studies 4, 156 p.

No abstract

Summary: This is a compendium of water-quality data, well construction information, and well logs for Griggs and Steele Counties. Includes map of well locations. Cited in other reports.

Bluemle, J.P., 1975. Geology of Griggs and Steele Counties, North Dakota, North Dakota Geological Survey Bulletin 64- Part 1 and North Dakota State Water Commission County Ground Water Studies 21 – Part 1, 156 p.

Griggs and Steele Counties, located at the eastern edge of the Williston basin, are underlain by 400 to 2,600 feet of Paleozoic and Mesozoic rocks that dip gently to the west. The Cretaceous Greenhorn, Carlile, Niobrara, and Pierre Formations lie directly beneath the glacial drift, and shale of the Pierre Formation is exposed in several places along the Sheyenne River. The Pleistocene Coleharbor Formation, which covers most of the area, consists mainly of glacial, fluvial, and lake sediment. The Coleharbor Formation averages 200 to 300 feet thick, but it is as much as 550 feet thick in some of the buried valleys. The Holocene Walsh Formation occurs in parts of the area, chiefly sloughs and river bottomland. It consists mainly of alluvial and eolian sediment.

Griggs Count and the western two-thirds of Steele County are part of the Drift Prairie, which is characterized by flat to gently rolling topography that is rugged in areas of end moraines and intense ice thrusting, subdued on the ground moraine and outwash plains. Associated with these major landforms are numerous washboard moraines, drumlins, eskers, kames, meltwater trenches, and water-washed areas. The eastern third of Steele County is a nearly flat area covered by lake deposits of the glacial Lake Agassiz.

As the Late Wisconsinan glacier in eastern North Dakota thinned and receded eastward, it was increasingly affected by the topography over which it was flowing. This resulted in lobation of the glacier. Locally intense areas of thrusting developed within the lobate glacier, and large blocks of subglacial material were moved short distances. Large areas of Griggs County were washed by water flowing from the glacier, and in some areas gravel and sand were deposited. Continued withdrawal of the glacier resulted in ponding of melt water in parts of the two counties. These and other ponds tended to coalesce at lower and lower elevations, eventually forming Lake Agassiz, which flooded part of eastern Steele County.

Downey, J.S., and Armstrong, C.A., 1977. Ground-Water Resources of Griggs and Steele Counties, North Dakota, North Dakota Geological Survey Bulletin 64- Part III and North Dakota State Water Commission County Ground Water Studies 21 – Part III, 33 p.

Griggs and Steele Counties, in east-central North Dakota, are underlain by bedrock of Ordovician, Jurassic, and Cretaceous ages. The Fall River and Lakota Formations of Cretaceous age form the Dakota aquifer. The fractured upper part of the Pierre Formation (shale), also of Cretaceous age, forms another bedrock aquifer. The Dakota aquifer, which consists mainly of interbedded shale and sandstone units, may yield as much as 500 gallons per minute (32 liters per second) of sodium sulfate water to wells at selected locations. The Pierre aquifer yields from 1 to 10 gallons per minute (0.06 to 0.63 liters per second) of sodium bicarbonate or sodium sulfate water to wells.

Four major glacial-drift aquifers are present in the study area. The Spiritwood aquifer system may supply as much as 1,500 gallons per minute (95 liters per second) of water to wells. Water samples contained dissolved-solids concentrations ranging from 244 to 9,800 milligrams per liter. The Galesburg aquifer will yield as much as 1,000 gallons per minute(63 liters per second) or water to wells. Water samples contained dissolved-solids concentrations ranging from 317 to 2,170 milligrams per liter. The McVille aquifer will yield as much as 500 gallons per minute (32 liters per second) to wells. Water samples contained dissolved-solids concentrations ranging from 449 to 2,200 milligrams per liter. The Elk Valley aquifer could yield 30 gallons per minute (2 liters per second) to wells. Water samples contained dissolved-solids concentrations ranging from 397 to 2,890 milligrams per liter.

Six communities in the project area use ground-water supplies. Rural water districts are being developed in the two-county area that will provide dependable ground-water supplies for many farms and small municipalities. The Spiritwood aquifer system and the McVille and Galesburg aquifers are capable of supplying the water needs of these districts and could also provide water for irrigation.

Downey, J.S., Hutchinson, R.D., and G.L. Sunderland. 1973. Ground-Water Basic Data for Griggs and Steele Counties, North Dakota, North Dakota Geological Survey Bulletin 64- Part II and North Dakota State Water Commission County Ground Water Studies 21 – Part II, 468 p.

No abstract.

Summary: This is a compendium of water-quality data, well construction information, and well logs for Griggs and Steele Counties. Includes map of well locations. Cited in other reports.